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MEASUREMENT OF THE PHOTOMETRIC PROPERTIES OF THE UPPER ATMOSPHERE

By J. M. WALDRAM, B.Sc., F.Inst.P. *(Fellow)*

Communication from the Staff of the Research Laboratories of The General Electric Company, Ltd., Wembley, England.

(Paper read at the Joint Meeting of the Illuminating Engineering Society and the Royal Meteorological Society, on Wednesday, March 21, 1945.)

(Paper received February 12, 1945.)

SUMMARY.

This paper describes the procedure in and the results of measurements made of the photometric properties of the atmosphere. The data were required for the solution of a number of visibility and similar problems ; the need for data is outlined, and the relevant photometric properties of the atmosphere are described. The experiments fall into two groups : measurements made in clean air, and those made in industrial atmospheres. In both atmospheres the polar distribution of light scattered by an element of the atmosphere was measured by polar nephelometers built for the purpose.

In the clean air measurements, a nephelometer was carried on an aeroplane and a series of flights was made, several up to 30,000 ft., over different parts of the country and at different times of the year. A series was also obtained at sea level on a ship. On one series of experiments several other measurements were made in addition, including the brightness of a searchlight beam measured from the air, and the air-ground transmission. Both these formed checks to the nephelometry.

In the industrial atmospheres a nephelometer was carried on an observation balloon. In these experiments the air-ground transmission was also measured carefully ; and it was possible to deduce from the results the absorption as distinct from the scattering coefficient. Three series of measurements were made over two industrial towns to heights of 3,000 ft.

The polar distributions of scattered light obtained varied greatly ; there appeared to be little correlation with altitude or with scattering coefficient in most cases, though one type of curve was usual on and near the ground. Some measurements were made in extremely clear air, when distributions not unlike the Rayleigh distribution were obtained. There is a hope that the size of the scattering particles might, in some cases, be deduced from the shapes of the curves.

In industrial atmospheres the absorption coefficient seems to be independent of the scatter, and there is a slight indication that it is small away from the vicinity of sources of pollution. Its amount is very variable.

The meteorological conditions for each flight are given in an appendix, and another appendix outlines other methods which have been tried for obtaining some of the data.

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Foreword

The work described in this paper forms a part of a programme undertaken by a Committee (Sub-Committee G: Photometric Properties of the Atmosphere; Civil Defence Research Committee) under the chairmanship of P. Good, Esq., C.B.E., and is published with official consent. The Committee included representatives of the three Services, of the Supply Departments, and of several Service Research Establishments; the Meteorological Office, the National Physical Laboratory, and the Research Laboratories of the General Electric Co., Ltd. The direction of the work described in this paper was in the hands of the author, but the work could not have been done without the active and cordial collaboration of many colleagues in his own and other establishments, who provided facilities and assisted in the experiments in many ways.

The author wishes to express his great appreciation of the help given by the following:—

The Director, Royal Aircraft Establishment, Farnborough, who provided and equipped aircraft and arranged flights; Mr. J. W. Sparke and Mr. H. F. Ringe, who took part in observations; S.Ldr. McArthur, D.F.C., R.A.F., and other pilots.

The Chief Technical Officer, A. and A.E.E.; and Dr. Hislop and his staff, who provided and equipped aircraft and arranged flights, and the Meteorological Research Council, who granted facilities for the use of their aircraft.

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Mr. M. G. Bennett, L.M.S. Railway, and Major Speir, L.M.S. Northern Counties Committee, who arranged special ground facilities in N. Ireland; and Mr. A. R. McGibbon and Mr. Watson and their staffs.

The Chief Superintendent, R.R.D.E., and Mr. D. E. H. Jones and his colleagues, who arranged for and operated a searchlight and assisted in ground observations.

Finally, Mr. P. Good, who personally arranged all the necessary contacts and made the whole work possible, and Dr. B. G. Dickins, Ministry of Aircraft Production, through whom the work was authorised.

With the exceptions noted in the text, the observations were made by the author and his colleagues, Mr. S. S. Beggs, Mr. P. H. Collins and Mr. J. W. Morse; the last-named made most of the air observations.

For reasons of security as well as from considerations of length, it is

not possible to discuss some aspects of this work; and the many applications which have already been made of the data cannot yet be disclosed. It is hoped in due course to discuss some of the related problems elsewhere.

I.—Visibility Problems and the Need for Knowledge of Atmospheric Properties.

During the war many problems of visibility have arisen, some of them of great urgency. With modern weapons, if the enemy can be seen he can be attacked; and if he is to be attacked economically and successfully he must be seen. Notwithstanding the extraordinary achievements of "radar," which can supplement and sometimes replace the eye, it is still necessary to see the enemy at some stage; and the man who can see has an enormous advantage. The references in the news to bad visibility, nightfall, smoke screens, and fog show that the war is a war of eyes; and problems of visibility in its broad sense have come not only to the meteorologist, who has to forecast conditions, but also to the illuminating engineer and to the designer of optical aids, who have to explain the mechanism of visibility, increase the range of vision, and provide light where necessary. The camouflage designer has the converse problem of making the enemy's eyes ineffective.

Seeing at long ranges is also becoming increasingly important in peace as well as in war, particularly as air transport expands. Even with all the aids available to the pilot and navigator for use when they cannot see, there are still stages in flying when they must be able to see; and visibility will doubtless remain important until designers of aircraft improve their performance by omitting windows for the pilot. Air travel provides the most striking and important example for the need for study of visibility; but there are many other problems, less spectacular but of great importance, in which the properties of the atmosphere play a large and often unsuspected part.

During the war many problems of seeing over fairly long distances have arisen, and have been tackled by Sub-Committee G or its predecessor committees, or otherwise. There were problems of seeing lights and signals and black-out escape; many problems involving the use of searchlights and flares; problems of terrestrial vision by day and night; of vision of the ground from the air; of air-to-air vision; and camouflage. The problems, and the methods of their solution, cannot be discussed here further than to say that experience showed the impossibility of making full-scale visibility experiments which were under control, and dictated the use, in general, of calculation and reduced-scale laboratory experiments in which all the relevant factors were introduced quantitatively and under control. The importance of the effects of the atmosphere became apparant at once, and a need arose for data of its photometric properties in the upper air as well as at ground level. The effects of the atmosphere could be correctly imitated in several ways, but there was no adequate information of their amount in nature.* A series of problems was hung up for lack of data; and it became necessary to set to work to obtain at least enough for work to be commenced. This paper records the work of getting the data and the results obtained.

Speed was very important. Some experimental risks had to be accepted, and many restrictions, which would certainly not have been tolerated in the calm of a peace-time research. The aim was to get as many data as possible, as quickly as possible, of an accuracy sufficient to avoid the drawing of false conclusions. Refinements had always to give place to speed. It is perhaps worth recording that the work was commenced as the result of a letter written to Mr. Good jointly by Dr. Stiles, of the National Physical Laboratory, and the author, dated November 1, 1940; and that the photometric gear was taken to Farnborough

* Rocard, Rev. d'Optique, 11, p. 193 (1932), gives a curve of polar scatter for the atmosphere at ground level.

Hulbert, J. Opt. Soc., Amer., 31 (7), p. 467 (1941), describes an indirect method by which the curve can be found at ground level, and gives a few examples; also curves derived from observations on a searchlight.

for installation on the aircraft for the first tests on January 21, 1941. In less than three months the methods of experiment had been worked out, new gear designed, and the apparatus made and tested. The first experiments were reported in May, 1941, seven months after the initiation of the work, and the last part of the work here described was reported to the committee on October 31, 1942, exactly two years after the initiation of the work. In the meantime much use had been made of the results as they came to hand.

It should also be recalled that the work was begun in 1940 at the height of the "blitz." This involved special difficulties in addition to those inherent in the problem, such as those of allocation of aircraft; of experimental flying, sometimes at night or above cloud; the need to avoid balloons, guns, and restricted areas; the need for radio silence and the difficulties of signals in war time; restrictions on the showing of lights; restrictions due to the movement of aircraft; the requirement that experiments should be made in areas unlikely to be raided; arrangements for getting down safely and extinguishing all lights in the event of a raid, and so on. These considerations restricted both the types of weather and the localities in which the experiments could be made, often to a very inconvenient degree; and for these reasons alone the results cannot be regarded as typical of all weather conditions and all localities. The experiments are rather an armed reconnaissance which has brought back some interesting information. It is hoped that the problem may be attacked in strength and systematically reduced if the results presented here are felt to justify further work.

II. Nature of the Photometric Properties of the Atmosphere.

In any problem of the projection of light or vision over long distances, the atmosphere introduces in general a twofold effect: an attenuation of all direct (unscattered) light passing through it, and—if the body of atmosphere is illuminated—the superimposition of a veil of scattered light over the scene. Both effects degrade contrasts and impair visibility. The distribution of brightness of the veil varies greatly according to the illumination conditions. Since transmission* varies exponentially with distance, the effect of the atmosphere may predominate at long ranges and is often the ruling factor in the problem.

The atmosphere is a turbid medium, and scatters light passing through it. The physical mechanism of scatter has been widely and fully discussed† and it is not the purpose of this paper to add to the theoretical discussion. The work described here was limited to the measurement of what actually occurs.

For the present purposes, it is sufficient to consider the atmosphere as containing numerous transparent spherical droplets of water (or dilute solutions of salts or acids) of various sizes and in various concentrations. These particles scatter light incident upon them; the size of the particle relative to the wave-length of the incident light determines both the amount of light scattered and its distribution in space. As Rayleigh‡ has shown, the molecules of the air themselves scatter light in addition to the particles suspended in the air. Particles of different sizes may be present simultaneously, and the incident light is generally white, not monochromatic, so that many modes of scatter will occur simultaneously. There may also be present particles of soot or other absorbing matter, which absorb light and possibly scatter it as well to a smaller extent. These particles may be independent of the water droplets. As will appear, in many cases absorption does not occur in significant amount.

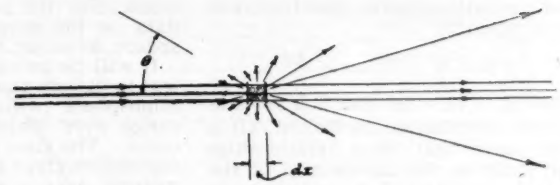
When a beam of light passes through an element of atmosphere of length dx (Fig. 1), a small amount of the flux in the beam is scattered by the element into various directions. The fractional rate of scatter is known as

* See p. 5.

† E.g., Ryde, Proc. Roy. Soc. (A), Vol. 131, p. 451 (1931). See also Middleton; "Visibility in Meteorology," second edition, Toronto University Press, where a very complete bibliography will be found.

‡ Rayleigh, Phil. Mag. 41, p. 447; Proc. Roy. Soc. (A), 84, p. 25 (1910); Proc. Roy. Soc. (A), 90, p. 219 (1914).

Fig. 1.



Scatter from element of atmosphere.

the scattering coefficient σ; it is the fraction of the flux scattered per unit length, or

$$\sigma = -\frac{1}{F}\frac{dF}{dx}$$

The scattered flux is not uniformly distributed in space, though it is disposed symmetrically about the direction of the incident light. In any direction, defined by the angle θ from the axis of the incident light, the element of atmosphere has a candlepower, i_θ such that

$$\int_{\omega=0}^{\omega=4\pi} i_\theta d\omega = -dF = \sigma F dx$$

where ω represents solid angle, or

$$2\pi\int_{\theta=0}^{\theta=2\pi} i_\theta \sin\theta \, d\theta = \sigma F dx$$

This candlepower i_θ has been termed the "polar scatter index." It is the candlepower in a stated direction of an element of atmosphere of unit length, receiving unit flux; and it is conveniently expressed in candles per foot per lumen (or—what is the same thing—candles per foot cube per foot-candle).

Thus it will be seen that the polar scatter index stands in relation to the scattering coefficient exactly as the candlepower of a lamp does to the flux emitted by the lamp; and the scattering coefficient can be obtained from the polar scatter index by integration, using zone factors, Russell's angles, or the Rousseau diagram or otherwise, just as flux emitted can be obtained from a candlepower curve.

There are theoretical reasons for expecting σ and i_θ to vary with the wavelength of incident light, and for the scattered flux to exhibit polarisation phenomena. Although provision was made in the apparatus, to be described, for the investigation of these phenomena, it was impossible to include the necessary observations, partly on account of time and partly from experimental difficulties. The present work is therefore confined to white unpolarised light.

When pure scattering occurs, all the light extracted from the incident light reappears without loss as scattered light. In that case, the flux remaining in the beam unscattered after traversing a length x of atmosphere is attenuated by a fraction t_σ, the transmission over the length x; by integration it can be shown that

$$t_\sigma = e^{-\sigma x}$$

When therefore pure scattering occurs, the scattering coefficient can be deduced from a knowledge of the transmission over a known distance and vice versa; but data of transmission do not give information about the distribution of the scattered light. When, however, smoke is present, a further phenomenon occurs; light is attenuated by absorption as well as by scatter, and the absorbed light is extracted from the beam without reappearing as scattered light. The phenomena of absorption and scatter appear to be independent. The absorption effect is expressed by an absorption coefficient , exactly similar to the scattering coefficient; and the transmission due to absorption over a distance x is given by

$$t_a = e^{-ax}$$

When both absorption and scatter

occur simultaneously the transmission is given by

$$t = e^{-(a+\sigma)x} \text{ or } e^{-Ax}$$

Where $A = (a + \sigma)$ and is known as the total attenuation coefficient. (It is to be noted that these relationships apply only to the attenuation of the original, unscattered beam; they do not apply to the transmission of diffused light through a fog, which is subject to more complex laws.) In many cases in practice absorption can be assumed to be absent, and pure scattering can be assumed to occur.

The relationship between transmission, range, and attenuation coefficient is given in Fig. 2. In this chart a series of curves relates transmission and range for various values of attenuation coefficient. There are several interesting features of this chart, which is very useful for calculations. It shows clearly how a given change in scattering coefficient may make only a small change in transmission over a short range, but a very large and important change over a long range. It is obviously inaccurate to deduce the transmission over a long range from measurements over a short one, or to deduce scattering or absorption coefficients from transmission measurements when the transmission is high. On the other hand, if scattering coefficients in clean air can be measured directly, it is possible to deduce transmissions from them with considerable accuracy, in a uniform atmosphere, down to values of transmission of 1 per cent. or so; lower transmissions are seldom important.

A disadvantage of measuring the scattering coefficient directly and calculating the transmission is that the scattering coefficient is found only for the place, or places, at which it is measured; unless the atmosphere is uniform over the range for which the transmission is required—or unless sufficient determinations are taken to ascertain the variation of scattering coefficient with distance—the calculated transmission may still not be correct. This disadvantage is felt mainly when the transmission is required for photometric work, or in connection with a particular experiment. For the purpose of collecting data on the properties of the atmosphere, however, it is of little moment.

It will be noted that it is meaningless to discuss the transmission of the atmosphere without specifying the range over which it is assumed to occur. The state of the atmosphere is sometimes given in terms of its transmission over a stated range; either per km. or per mile or per 1,000 yds. In meteorological work, the unit of the "nebule" has been proposed by Gold* and is often used. After due consideration, the Committee decided against its use in this work; for the data are required mainly for calculation of illumination problems, and it is more convenient to have the results in terms of transmission. It may however be useful to indicate the relationship between the data given here and the meteorological visibility range as commonly used and quoted by meteorologists. This quantity is defined as the greatest range at which a large black object can be seen in daylight against the horizon sky. It can be shown from Koschmieder's equation† that the transmission of the atmosphere at the daylight visibility range is equal to the least relative brightness difference which the eye is capable of perceiving, or about 2 per cent. in daylight. If therefore on Fig. 2 a horizontal line is drawn at the value of 2 per cent the daylight visibility range corresponding to any scattering coefficient can be read off; and similarly, knowing the visibility range the scattering coefficient and the transmission to any less range can be found, by following up the curve corresponding to that scattering coefficient. The visual range for any other condition, e.g., at night, can be found by drawing a line at a transmission equal to the just

* Gold, Quart. J. Roy. Met. Soc., Vol. LXV., p. 139 (1939). A "nebule" is a unit of opacity, such that 100 nebules reduce the direct transmission to 1/1,000. The fraction of light transmitted through one nebule is thus 0.933. The opacity of the atmosphere is stated, by this system, in nebules per km. (or other convenient distance). The "nebule" is analogous to the "decibel"; 1 nebule = ¼ decibel approximately.

† See Middleton, "Visibility in Meteorology," 2nd Edition, p. 37.

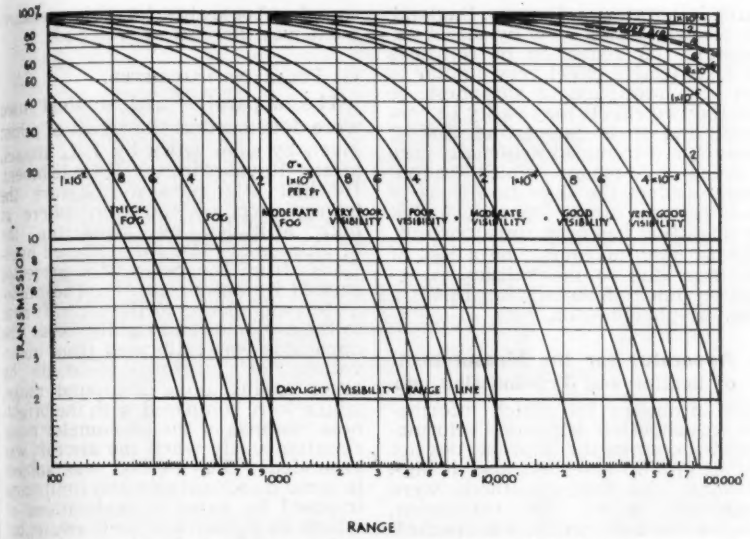


Fig. 2. Transmission, Range, and Scattering Coefficient.

perceptible relative brightness difference, for the condition concerned, if it is known. The scattering coefficients corresponding to the standard descriptions of meteorological visibility can be read from Fig. 2.

The kind of information required about the atmosphere in practice varies with the problem. Often the transmission alone is sufficient, e.g., in problems of vision of distant lights at night. In other cases knowledge of the approximate polar distribution of scattered light is necessary, as in some calculations of the brightness of illuminated haze layers; but where the haze is illuminated by artificial light relatively strongly—for example in problems of searchlights and flares—it is often necessary to know the polar distribution in detail. Knowledge of the polar distribution will enable a comparison to be made with distributions calculated from theory and may very possibly yield information about particle size in some cases.

Obviously, if the polar distribution of scattered light is measured, the scattering coefficient and (in clean air) the transmission can be calculated and the greatest amount of information will be obtained. Fortunately, it is probably more accurate to derive scattering coefficients from polar distributions than to measure them directly, since a smooth distribution curve is drawn through observed points; and it has just been shown to be more accurate in uniform clean air to derive transmissions from scattering coefficients than to measure them directly. Other advantages of seeking to measure the polar scatter index will appear. This measurement was made the main target of this investigation as being the most useful, most accurate, and most convenient measure of the properties of the atmosphere.

It has been thought by some investigators* that there is a further optical effect of the atmosphere—that it diffuses the optical image of distant objects and makes outlines less well defined. There is a popular supposition that this is so, and artists sometimes draw distant outlines as not sharp with this apparent effect in mind. The author believes that this effect does not really occur in significant amount; and some recent unpublished work by Barber, of Kodak Re-

* Middleton, loc. cit. p. 64. Bennett, Quart. Jour. Roy. Met. Soc, LVIII., p. 259 (1932); LXI., p. 179 (1935).

search Laboratories, Harrow, England, has confirmed this view by direct experiment. A reduction of contrasts has a subjective effect very similar to that of a reduction of sharpness, so that the two effects may easily be confused; and it is interesting that if "haze" is introduced artificially into a scene by means which cannot possibly affect the definition there is nevertheless a strong impression that the definition has been impaired.

There may, of course, be a loss of definition due to inequalities in refractive index of the air; but this is a different phenomenon.

III. Apparatus for the Measurement of Scatter and Transmission, etc.

The problems for which information was required demanded information of the atmospheric properties not only at ground level but also at high altitudes; and many methods were considered before the conclusion, stated in the last section, was reached. Mr. E. Gold, F.R.S., of the Meteorological Office, gave the valuable advice that observations, say of transmission made from the ground to successive heights in order to find the transmissions in upper layers, would be vitiated by the relatively great amount of scatter likely to be found near the ground, and by the changes likely to occur there. Reliable information of conditions in the upper air could only be obtained by going up to get it. This involved observations made from an aeroplane at various altitudes.

The Committee was at that time much concerned with transmission as such, rather than with scatter; but it became obvious that the transmission of the atmosphere over a known distance at a given altitude could not be measured successfully from aircraft for many practical reasons. It would involve two aircraft keeping station at night, at accurately known range, which alone is extremely difficult to arrange, apart from the instrumental difficulties. Measurement of scatter, however, could be made by a self-contained and small apparatus which could be operated by one observer in one aircraft, an advantage even greater than those of increased accuracy and usefulness already stated. Apparatus for this measurement was therefore developed.

(1) Polar Nephelometer.

The apparatus and method used were developed as the result of a hint given by some work by J. L. Russell at the Royal Aircraft Establishment. He had attempted to measure the transmission of the atmosphere at high altitudes by measuring the brightness of the light scattered backwards from the beam of a projector carried by an aeroplane. The photometer was placed in the aircraft near to the projector and rigidly fixed. The apparatus was calibrated from observations of transmission made by other means along a ground range, which were compared with the brightness readings of the photometer made simultaneously when the aircraft was grounded. This method was subject to some disadvantages and limitations imposed by other considerations, of which its author was well aware, but which could not then be avoided; and for some time his three ascents provided the only photometric data of the upper atmosphere.

Inspired by this attempt, an apparatus was developed which is shown in its final form in Fig. 3, and diagrammatically in Fig. 4. The complete description of the instrument will, it is hoped, be published separately. The principle is briefly as follows: Light from a 240-watt lamp (A) is condensed by an ellipsoidal mirror (B) and brought to a focus at an aperture (D), formed in a screen and measuring $\frac{3}{4}$-in. wide by $\frac{5}{8}$-in. high. A slightly diffusing glass (C) is used to reduce striation of the beam at the aperture.

A visual photometer (P) is arranged to measure the brightness of the beam as it emerges from the aperture. Since the brightnesses concerned are very low, a black light-trap (T) is placed behind the part of the beam viewed; the brightness of this trap is negligible, and the photometer is so designed that it cannot see anything else. Light from the lamp is very carefully screened and cannot reach the photometer or the light trap. The whole assembly of screen, aperture, photometer, and light trap can be rotated about an axis at right angles to the beam on a

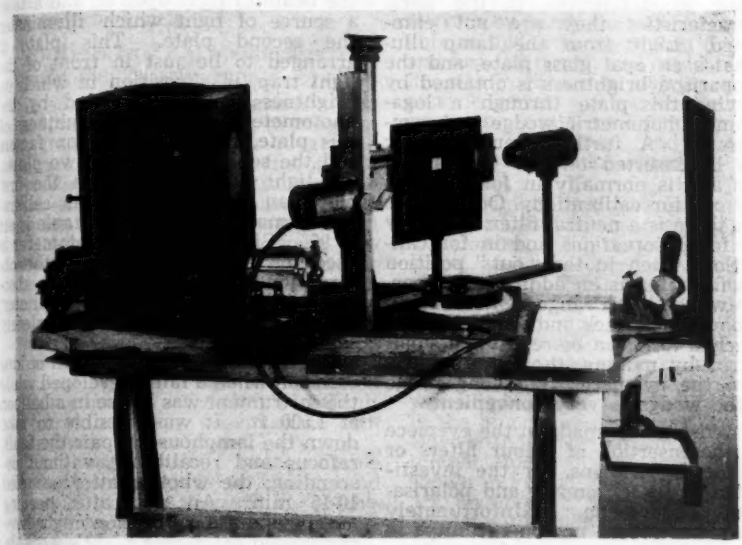


Fig. 3. Mark II(b) nephelometer erected on board used on the balloon (without telephotometer).

turntable; the screen rotates about an axis offset from that of the photometer and is driven by gearing. Thus the photometer can measure the brightness of the beam at all angles, except within 15 degrees of the axis of the beam, and the polar scatter index can be calculated from the photometer readings.

Since the aperture is rotated, the light flux in a uniform beam would be varied as the sine of the angle of view. It happens that a sine term enters in the calculation of the polar scatter index, and it is convenient to introduce it mechanically in this way, for the rotation of the screen is most desirable for reasons of screening and mechanical design. Slight non-uniformity of the light beam introduces small deviations from a sine curve which have been determined and are allowed for at each angle.

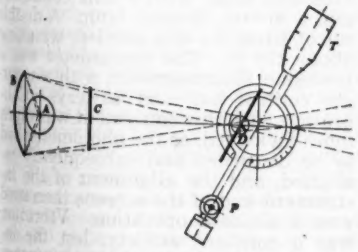


Fig. 4. Polar nephelometer optical system.

The photometer finally used was designed for the apparatus. It is a simple visual photometer with a 6-deg. bipartite field and a 7.5 mm. artificial pupil, so that it is suitable for low-brightness observations.

To avoid stray light optical parts are reduced to a minimum; there is one lens and a prismatic field of simple design consisting of two prisms cemented together, one half of the interface being silvered. Two stops are so placed with respect to the lens that images are formed of them, one at the mouth of the light trap and one opposite to the aperture in the screen at D.

The comparison lamp, a 4-volt 8-watt krypton filled miner's lamp, is run from a potentiometer connected across the main lamp; this arrangement reduces the effects of fluctuations of the supply voltage, though

owing to differences in the lamp characteristics they are not eliminated. Light from the lamp illuminates an opal glass plate, and the comparison brightness is obtained by viewing this plate through a logarithmic photometric wedge and compensator. A further neutral filter can be inserted on the comparison side and is normally in for readings and out for calibration. On the test side there is a neutral filter, normally out for observations and in for calibration; when in the "out" position this filter forms an additional screen. The wedge has a range of 1,000:1 and is moved by a rack and pinion; a scale attached to it can be read via a small mirror by moving the eye slightly from the eyepiece. The long range of the wedge is very convenient.

Provision was made in the eyepiece for the insertion of colour filters or "Polaroid" screens, for the investigation of the chromatic and polarisation phenomena. Unfortunately there has been no opportunity to make the necessary observations, which are in any case difficult on account of the very low brightnesses which occur. Even had they been simple to make, the complication in the procedure would have been prohibitive.

In the early stages of development of the nephelometer a photoelectric method was tried; but it was evident that the method was insufficiently sensitive. Even had the sensitivity been sufficient, however, there would have been the problem of developing very sensitive photoelectric gear which would be satisfactory in the air. There can be little doubt that had the idiosyncracies of photoelectric and electronic devices in their development stages been added to all the other troubles of these experiments, no results would have been forthcoming at all.

In order to calculate the polar scatter index, it is necessary to know the flux of light in the beam. An attachment enables this to be measured by the same photometer very simply. A bar is clamped to the turntable, carrying two white matt opal glass plates fixed parallel to each other at a known separation. The larger one is so located as to receive the whole of the beam of light upon it, and acts as a source of light which illuminates the second plate. This plate is arranged to lie just in front of the light trap, in a position in which its brightness can be measured by the photometer. From the brightness of this plate, the two reflection factors and the separation of the two plates, the light flux falling upon the first plate can be calculated. This calibration is made when the turntable is set at 90°. Since the same photometer is used for the calibration and the observations, there is no need for absolute calibration of the photometer, and the instrument is thus completely self-contained.

The value of this was shown on one occasion when a fault developed while the instrument was in use in a balloon at 1,500 ft. It was possible to take down the lamphouse, repair the fault, refocus and recalibrate, without descending; the whole matter occupied 10-15 min. An apparatus needing more elaborate calibration might have prejudiced the whole night's work. In any case, in the difficult experiments which are described later, there is great advantage in a calibrating attachment which enables the instrument to be checked frequently.

The apparatus measures 20 in. x 22 in. x 14 in. high overall (allowing for the swing of the turntable), and its weight is 36 lb., including a voltmeter and resistance. It is run from an aircraft battery (12 volt, 36 amp. hrs.), weighing about 36 lb.; this is sufficient for one night's work, involving eight or more curves. A polar curve can be taken in about 6 min, including calibration.

This is the final form of the apparatus. On the earlier investigations, a preliminary and much clumsier apparatus was used, with a lens condenser and a 30 volt, 30 amp. lamp. A double set of batteries was carried, weighing about 270 lb. The photometer was a precision illuminometer, with a separate control box and battery. Calibration with this equipment was much more awkward, as the photometer had to be disturbed and subsequently realigned, and the alignment of the instrument and of the screens then used was a delicate operation. Vibration was a constant anxiety, lest the instrument should be shifted; it never

did, but the adjustments had to be checked frequently.

(2) Apparatus for Measurement of Air-Ground Transmission.

In some of the experiments to be described, it was decided to measure the transmission from air to ground for various heights. Since it would be possible to calculate this transmission from the nephelometer observations, the overall transmission measurement would provide a check and would give evidence about the presence or absence of absorption. The decision was not altogether wise, for if two methods are to form a satisfactory check on each other they should be of at least comparable accuracy; and as will appear the transmission measurement is exceedingly difficult to carry out from considerable altitudes from an aeroplane.

The simplest and most suitable method* of measuring air-ground transmission is to measure the brightness of an extended surface on the ground, by an airborne instrument. The transmission is the ratio of two readings, one taken at close range and the other from the distant point; the distance does not enter into the calculation, and the photometric range is short so that scale errors are minimised. No absolute calibration is required. The difficulty is to provide an instrument capable of measuring a surface of reasonable size from the greatest height concerned and in the conditions of vibration and discomfort inseparable from observations from aircraft.

It happened that a small telephotometer was avilable of the telescope type† in which the observer sees an image of the distant view, including the target; and, included in the field, a small patch the brightness of which he can control. It was found by experiment that this instrument should enable observations to be made on a 40 ft. white sheet on the ground. It was designed for use on a stand, and for the present purpose it had the disadvantage of having a very small and inverted optical field. This made the instrument particularly difficult to train by hand; the observer inevitably moved it in the wrong direction and lost the target, and could not find it again in time. It was found from experience that a single observer in an aeroplane could not simultaneously train the instrument and make the photometric balance when the target was small.

Accordingly, an arrangement was used in which two observers took part, one training the instrument on to the target while the other performed the photometry. The training observer used a pair of field glasses having a small luminous spot in the field, and the axes of the binoculars and of the photometer were set parallel so that when the image of a distant object was aligned with the luminous spot in the binoculars, its image also coincided with the comparison patch in the telephotometer. The gear used is shown in Fig. 5. The two instruments are clamped in fixed positions in a frame with their axes parallel, and view the ground through two plane mirrors of good quality. The first is fixed, and the second is on a ball

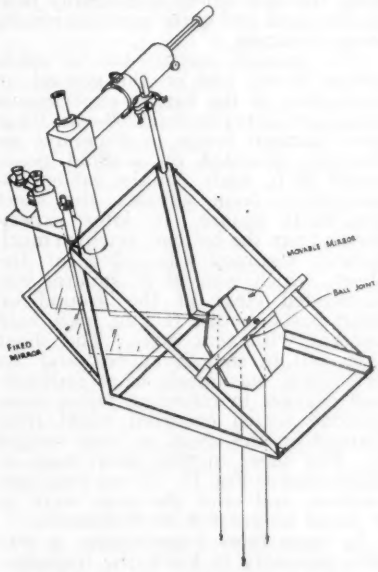


Fig. 5. Telephotometer apparatus.

* See Collier, L. J., Trans. Ill. Eng. Soc. (London), 43 (10), p. 141 (1938).

† Waldram, J. M., Illum. Engineer, 27, p. 311 (1934). (This describes an earlier form of the instrument.)

joint; the training observer places his hand on this mirror and moves it about to find and aim at the target.

Even with this arrangement, the measurement is one of great difficulty. There is considerable vibration, and the image is never steady in the field of view; the aircraft is liable to lurch and bump at critical moments. The balance should be made as the target passes beneath the aircraft; it is then necessary to wait while the aircraft turns and makes another run before another balance is possible. The target, at the greatest altitude of observation (18,000 ft.) is very small, it subtends only about 7 minutes of arc, or about the size of a full stop in these Transactions.

In later experiments to be described, similar observations were made from much lower altitudes (3,000 ft. maximum) from a balloon. In this case the complication of the second observer was unnecessary; there was no vibration, and the target remained stationary so that the observer could take his time, and the subtense of the target was very much greater. For these observations, therefore, the instrument was simply held in the hand and quite accurate results were obtained.

The ground target was a white cotton sheet, laid on the ground on tarpaulins in the earlier experiments and illuminated by four 200-watt tungsten filament lamps in dispersive reflectors, mounted on scaffold poles, about 20 ft. high. In the earlier experiments, from aircraft, the sheet was 40 ft. square. In later experiments from the balloon, in which much greater accuracy was called for, the sheet, which was 20 ft. square, was suspended clear of the ground on short posts about 2 ft 6 in. high, held upright with tent guys. The sheet then fell in smooth curves, and its brightness was much more uniform; and changes in reflection factor were avoided which occurred when frost formed on the sheet or dew wetted it. The sheet in this latest form is illustrated in Fig. 17. It was very convenient, and once the pegs were in it could be erected in 10 minutes.

In these later experiments, it was also necessary to know the transmission of the air at ground level. This was determined by observations with the same telephotometer, mounted on a tripod with a traversing head, and observing a target consisting of a copper hemisphere painted matt white inside and illuminated by a small 12 volt, 36 watt opal bus lamp mounted at its centre; a small screen obstructed the view of the lamp itself. The brightness of this hemisphere was very nearly uniform, and it was successfully observed at a range of 900 ft. It can be seen in the photograph of Fig. 18. It was placed in the back of a small van and run from the van battery through a special circuit with rheostat control.

(3). Low Brightness Photometer.

In one experiment it was decided to measure the brightness of the beam of a searchlight, exposed vertically, from an aircraft as it flew past the beam at known altitudes. The beam brightness was low, and there were no suitable photometers available for its measurement. A special instrument was therefore constructed for the purpose, which will be only briefly described here.

The instrument is shown in section

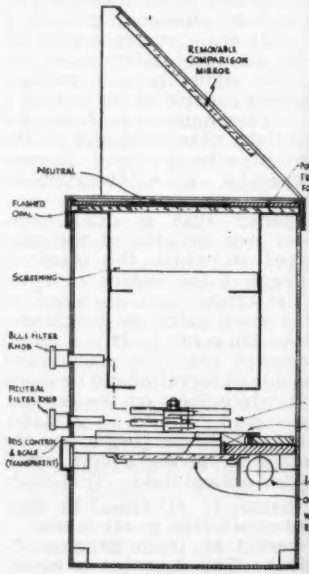


Fig. 6. Low brightness photometer.

in Fig. 6. It consists of a rectangular box, divided into two compartments by a horizontal partition bearing an opal glass on its lower side and an iris diaphram on its upper side. The iris thus provides an aperture of variable size, over the opal, which is illuminated by a small screened lamp in the lower compartment. This aperture acts as an illuminator for a second opal glass mounted in the top of the box; there is a screening system to prevent reflections from the sides. A mask is placed over the opal so as to leave a 2 in. square visible from above, and over this square is a piece of neutral glass having a transmission of about 0.05. Around the square is a border of dense white matt opal glass, which forms a test surface and enables the instrument to be used as an illuminometer; the brightness of the border, illuminated by light falling on the box, is matched against that of the centre square. The neutral glass has a double function: it reduces the brightness of the central square to the desired range, and it also acts as a light trap, preventing the test illumination from affecting the brightness of the comparison surface. Any light falling upon the comparison surface has to pass through the neutral glass twice.

To use the instrument as a brightness meter, the opal border is ignored and an attachment is added having a strip of mirror, about 1 in. wide and 3 in. long, set at 45 deg. at the top of the instrument. The mirror reflects the brightness of the central comparison surface, and the brightness of distant objects is obtained by matching them with the brightness of this image. The edge of the mirror forms the photometric boundary; it is vertical and forms a very suitable means for measuring the brightness of the vertical searchlight beam, provided that the beam is not too far distant.

Two filters, a neutral and a blue, are provided which can be inserted in the comparison side at will. The lamp is fed from a battery and controlled by a rheostat and voltmeter in a separate control box.

The instrument allows the free use of the eyes without artificial pupils, and provides a large photometric field. It was convenient and easy to use, and enabled measurements to be made of brightnesses of a few millionths of an equivalent foot-candle from the air without difficulty; the observer could go to either side of the balance point with certainty. Its range is from about 5×10^{-6} to 5×10^{-3} equivalent foot-candles.

IV. Measurements made in Clean Air

Three series of measurements have been made from aircraft in air believed to be free from industrial pollution and to heights up to 30,000 ft. A fourth series was made at ground level. The first series was by far the most elaborate, and it will be described in some detail to give an indication of the organisation of experiments of this kind.

(1) *First Series: Spring*

The first series of observations was commenced in January, 1941. Trouble with the aircraft delayed the start, and an expedition started for Northern Ireland, where the experiment was to be made, on February 24, 1941. This expedition was, however, unsuccessful, owing to further trouble with the aircraft. After some further delays, a Wellington Ic aircraft was allotted to the work; the apparatus was improved and installed, and a party left for Northern Ireland in the Wellington on April 23. Northern Ireland was made the base for the trials partly for operational reasons, for it was necessary to find an area likely to be free from air raids; moreover, it was desired to make some further observations on other experiments, in the course of the atmospheric flights, for which the ground gear was already installed in that neighbourhood. For technical reasons Ireland was not so suitable, for the atmosphere there has the reputation of being unusually clear; but that could not be helped. Fortunately, very clear air was not encountered in the experiments. But by the time the experiments had commenced, air raids had reached the region and interfered with the work to some extent.

(a) *Experiments planned*

The following experiments were planned on the atmospheric work:—

(i) Nephelometry of atmosphere.

(ii) Measurement of air - ground transmission.
(iii) Measurement of brightness of a vertical searchlight beam, at two values of arc current.
(iv) Observations with Russell's method.
(v) Measurements of sky and ground brightness.
(vi) Psychrometer observations.

All the above observations were to be made at a series of altitudes from the ceiling of the aircraft downwards, at intervals of 5,000 ft. It was intended to make some observations of a visibility experiment in addition.

Such a programme of observations in an aircraft involves the most careful organisation if it is to succeed. It is a tribute to all the many collaborators who helped both in the air and on the ground that the programme was completed and was in the main successful.

The party was as follows:—

(Air)

Mr. J. W. Sparke (R.A.E.): Recorder and liaison.
Mr. B. H. Crawford (N.P.L.): Observer for visibility experiments.
Mr. J. W. Morse and Mr. J. M. Waldram (G.E.C. Research Laboratories): Observers for atmospheric experiments.
S/Ldr. McArthur, D.F.C., R.A.F. (R.A.E.): Pilot.

(Ground)

Mr. A. R. McGibbon (L.M.S. Railway); Mr. Marshall (N.C.C.) and staff: Visibility experiment and telephotometer target.
Mr. D. E. H. Jones (R.R.D.E.), and three colleagues: In charge of searchlight and ground observations.

(b). *Installation of Apparatus in Aircraft.*

The apparatus was installed in the aircraft by the Royal Aircraft Establishment. As originally planned, the experimental gear was concentrated amidships, with the intention that two observers there could work all the instruments, reporting their readings by telephone to the recorder who would be seated at the observer's position, where there was a suitable desk, lighting, etc. The observations on the searchlight beam were to be made from the astral dome further forward.

This arrangement was used for the first flight, which was, however, unsuccessful, as the marker flares were too weak and could not be seen. On a second attempt a collision occurred with another aircraft on the ground, and the Wellington was rendered completely unserviceable. The following night a Battle aeroplane was made available, and Mr. Crawford and the writer made an attempt to make the visibility observations, but an air raid occurred and the flight was interrupted. Next day, as the result of arrangements made by Mr. Good and Dr. Dickins, another Wellington was allotted to us; but it was necessary to remove all the fixings and apparatus from the original aeroplane and transfer them to the new one; this was a big undertaking. The new machine was a later mark and differed sufficiently from the old one to make it impossible to fit the telephotometer amidships, but with the aid of a bracket made by the maintenance unit at the aerodrome, it was fitted in the bomb-aimer's position in the nose. The gear was successfully transferred by Mr. Sparke, Mr. Morse, Mr. Crawford, and the writer, using the resources of a laboratory tool-box. Enough was installed on the first day for a successful observation flight that night; observations were also made on the searchlight. The weather was unsuitable for flying on the next two nights, but the installation was completed and a day test flight made. On May 1 and 2 two complete flights were made, the first successful except for the telephotometer observations, and the second entirely successful.

The installation of the gear in the aeroplane, as actually used, is shown in Fig. 7 and in the photographs Figs. 8 and 9. The nephelometer was mounted on a board together with the necessary resistances, switchgear, and voltmeter; the batteries, which were provided in duplicate, were placed forward on the other side of a main frame. The photometer control box was fixed on the lower floor.

Air from outside was led to the nephelometer by a pipe, which at its outer end faced forward and was arranged to pass the air to the point

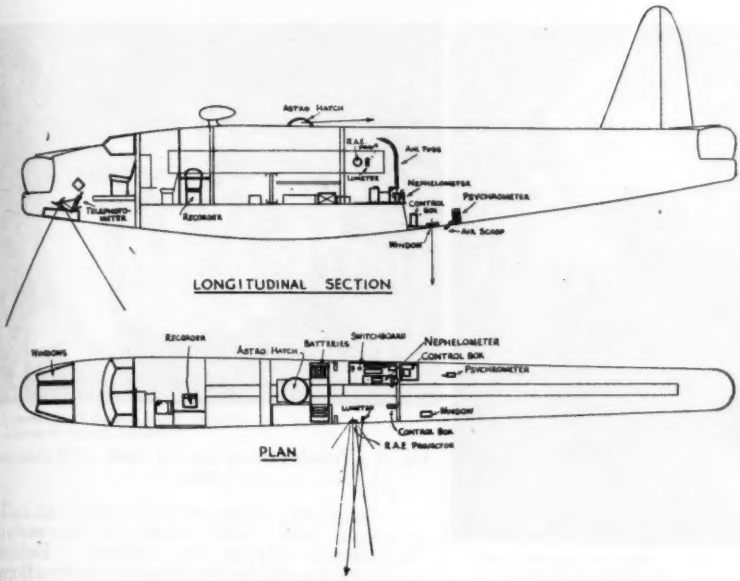


Fig. 7. Arrangement of apparatus in aircraft.

at which measurements were made with as little disturbance as possible. It was realised that if changes of pressure occurred, the physical state of the air might be altered; and the pipe was lagged and arranged to cause little change to the pressure or temperature. Later information showed that the arrangement first used was far from ideal, and on the later series (Series III) a much improved air pick-up was provided. Nevertheless, there seems no reason to suppose that the air suffered serious change even on the first tests, as the independent checks were satisfactory.

The Russell apparatus, made by R.A.E., was mounted on a plate in one unit and arranged to project the light beam from one of the side windows. It consisted of an aircraft landing projector, rigidly mounted and permanently focused, and a Holophane Lumeter, modified to have a large divided field and fixed to view the beam from a position about 1 ft. from its axis. The projector was run from the same batteries as the nephelometer and the same voltmeter was used. The psychrometer was fixed aft of the nephelometer control box, and received air from an air scoop.

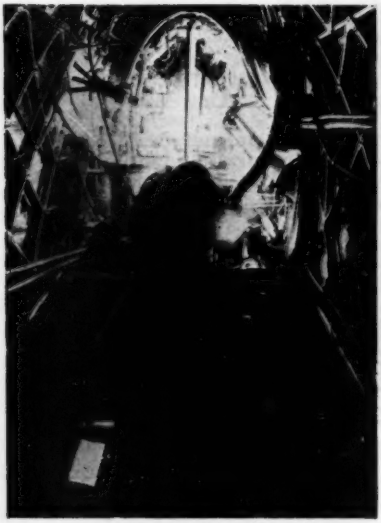
A small perspex window was made in the floor, opposite to the psychrometer, for the measurement of ground brightnesses.

The location of the telephotometer in the bomb-aimer's position in the nose involved several difficulties; the position was designed for one man, and it was very uncomfortable to have two observers there. There were also difficulties about telephone and oxygen points for the second observer; and, finally, in the provision of the extra observer himself. Mr. B. H. Crawford, of N.P.L., volunteered to act in this capacity, although he had come only for the low-altitude work and had no flying suit.

The photographs Figs. 8 and 9 show the equipment amidships in the aircraft and the telephotometer in the nose respectively.

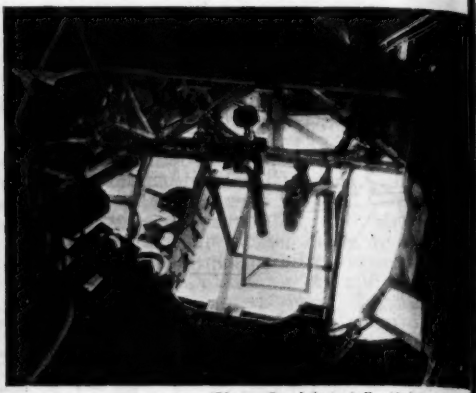
(c) *Procedure.*

The tests were arranged as follows: Mr. J. W. Sparke acted as controller,



[Photo. Royal Aircraft Establishment: Crown Copyright Reserved.]

Fig. 8. Observer using nephelometer in rear of Wellington bomber. The Russell apparatus can be seen on left top: Nephelometer control box and psychrometer right foreground at observer's feet, window left foreground. The astral dome is in roof in background.



[Photo. Royal Aircraft Establishment: Crown Copyright Reserved.]

Fig. 9. Telephotometer gear in nose of Wellington bomber.

with the duties of recording all observations, seeing that all were completed, giving instructions to the observers and to the pilot, and instructions for signals to ground. He had no observations to make himself. The provision of a controller on intricate field tests has been found to be of great value, and on such a test as this it was essential. Mr. Crawford and Mr. Morse operated the telephotometer in the nose. The writer operated the nephelometer, Russell apparatus, and other gear amidships and took observations on the searchlight.

The aircraft took off in the late twilight, and proceeded to the test area, which was defined by two paraffin "Money" flares on the ground; a climb was made to ceiling, which in this aircraft was only 18,000 ft. owing to slight trouble with engines. Observations began at ceiling and were made at successive levels during the descent. Before taking off, nephelometer observations were taken and a reading on the Russell apparatus. At each level, the schedule shown in Table I was carried out.

This programme was carried out at 18,000 ft., 12,000 ft., 7,000 ft., 4,000 ft., and 2,000 ft. On returning to base, observations were taken at ground level with the nephelometer and Russell apparatus, and the nephelometer was recalibrated. The ground team measured the brightness of the white target during the observations, using a photometer later checked against the telephotometer.

The observations at each level, and the descent to the next level, required about 30 min. The time of each observation was logged both in the air and on the ground, as a precaution against getting out of step. For operational reasons, radio could not be used for communication, so light signals were given by the aircraft landing lamp directed vertically downwards.

(d) *Experimental conditions.*

(i) *Personal.*—In assessing the results of the experiments and the design of the tests, it is necessary to realise the conditions under which observations have to be made. They are

Table I.

	Ground Team	Aircraft	Signal	Front Observers	Rear Observer
1st Altitude	Expose S/L Current A	Run past S/L	—	—	*Measure beam brightness, Current A*
		—	Signal to ground	—	
	Dowse S/L				*Measure Sky Brightness*
	Illuminate target	Make runs over target	—	*Measure Target Brightness*	(Disconnect and return to rear position) *Measure Ground Brightness.*
	Change carbons for Current B.	,,	—	,,	*Read Psychrometer* (Reconnect) *Nephelometer Observations* *Russell Apparatus Observations*
	,,	,,	—	,,	
	,,	,,	Signal to ground	—	(Move to dome)
	Dowse target		—	—	,,
	Expose S/L Current B	Run past S/L	—	—	*Measure beam brightness, Current B*
	,,	Descend to next altitude	—	—	(Remain at dome)
2nd Altitude	,,	Run past S/L	—	—	*Measure beam brightness, Current B*
	,,	,,	Signal to ground	—	
	Dowse S/L		—	—	*Measure sky brightnesses*

And so on.

familiar to those used to aircraft, but are seldom recorded for the guidance of others. The photometry was of a kind which is difficult even in laboratory conditions; brightnesses were often low, and the telephotometry would have been far from easy even with the instrument on a rigid stand. In the air, the conditions make good photometry very difficult. The observers have to wear heavy flying suits, gloves, and flying boots, and a parachute harness which makes bending and movement difficult and slow. Helmets and face masks are worn with telephones, phone leads and oxygen pipe; the latter restricts movement considerably, and had to be disconnected and reconnected whenever the observer moved from one position to another. One observer wore a cap lamp, which was invaluable but involved another wire. The noise is such as to make conversation without telephones impossible; readings must be passed by the intercommunication telephone, and the speech quality is often not very good, so that all readings must be passed slowly and called back. The use of oxygen is important as anoxia causes a rise in the visual threshold, and at 18,000 ft. it

is necessary in any case; to move down the machine in flight from one oxygen point to the other, carrying the photometer, is surprisingly exhausting.

(ii.) *Vibration.*—The main difficulty is vibration and the movement of the aircraft. Vibration is serious, and instruments not designed to withstand it may suffer. Anything loose must have a proper stowage, or it falls down and is lost or is trodden on and damaged. All gear must be fixed down for safety, for in a heavy bump it might damage itself or the aircraft. Instruments may become unclamped or go out of alignment. The taking of photometric observations in these conditions is very trying, particularly with the telephotometer, for the target image is never steady. Rubber eyepieces were necessary, not only to exclude light but also to protect the eye in bumps and to act as thermal insulation.

(iii) *Temperature.*—The temperature becomes very low at high altitudes, and this may affect the apparatus as well as the observers. There was cabin heating on this aircraft, but it was turned off during nephelometry as a precaution. At low temperatures the observer tends to freeze to the eyepiece, or to any other metal surfaces; batteries lose capacity, and dry batteries lose volts; and on descending glass surfaces may frost over so that optical apparatus becomes unusable. On the first series, therefore, heating jackets were provided for two of the photometers, and batteries were lagged as far as possible. Two main batteries were provided as a precaution. Actually, little trouble was experienced with low temperatures on this series of experiments; but in later experiments it was more serious.

(2) Second Series: Autumn-Winter.

In October and December, 1941, it became possible to make further ascents in a Wellington aircraft capable of flying to much greater altitudes and carrying the nephelometer only. The instrument was substantially the same as that carried on the first series. The flights were made in daylight, the interior of the aircraft being blacked out as the photometer field brightness was very low. These observations were made by Mr. J. W. Morse and Mr. P. H. Collins. On these flights the temperature was very low; the air temperature, by the aircraft thermometer being as low as – 42 deg. C. on one occasion. In the cabin it was extremely cold and the observers were in considerable discomfort; no bare metal could be handled, and it was necessary to observe only on the ascent, because on the descent all glass surfaces frosted over. Four ascents were made, to altitudes of closely 30,000 ft. The polar distributions obtained were very different from those in the first series, and showed some most interesting types;

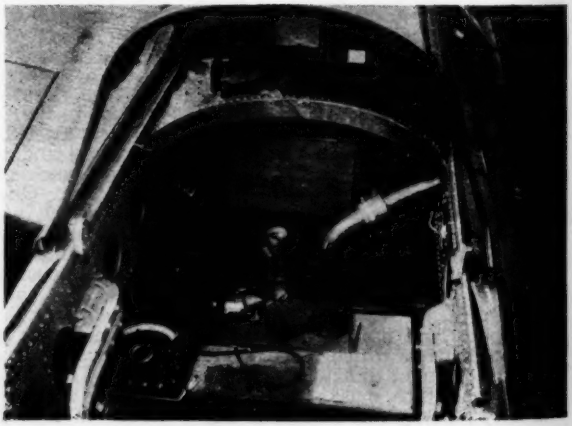


Fig. 10.
Nephelometer in Boston bomber.

[Photo. Royal Air Force, Crown Copyright Reserved.]

the results are discussed below. These curves were obtained over various parts of England.

(3) THIRD SERIES: SUMMER.

In May, 1942, it became possible to make a further series of high flights, this time by collaboration with A. and A.E.E. in a Boston III aircraft which was flying on experiments for the Meteorological Research Council. A new nephelometer had been built, of the type shown in Fig 3 and running from a single battery, and the instrument was placed in the rear position in the Boston, where it could be worked by a single observer. The air pick-up was much improved, on the advice of A. and A.E.E., and consisted of a single 2½-in. copper tube facing the relative wind clear of the fuselage and in a region as free as possible from turbulence. The apparatus in position is shown in the photograph, Fig. 10. Seven ascents were made in daylight with this apparatus, to 30,000 ft. in May and June, 1942. Very interesting results were again obtained, in both extremely clear conditions and in slight hazes extending to great heights, over various parts of England; the results are given below. The observations were made by Mr. J. W. Morse.

(4) FOURTH SERIES: SEA LEVEL.

In January and February, 1942, it became necessary to determine the atmospheric properties during some trials at sea, and a nephelometer was taken on a ship, placed in a small chart-room with a door at each end so that the air could pass freely through the room. A large number of polar distributions was taken during these trials, one set of which is given below. Since then the nephelometer has been loaned to H.M.S. Vernon, who have taken many more sea-level observations with it. During the sea trials it was noticed that if one of the doors was accidentally closed the readings immediately became erratic—a tribute to the sensitivity of the nephelometer.

(5). RESULTS IN CLEAN AIR.

(a) *Polar Scatter Index.*

The polar distributions obtained in clean air in the four series of observations described above are shown in Fig. 11 (a-n). Only one set is shown from the fourth series. The distributions are such that they cannot be usefully plotted on polar co-ordinates, and they are therefore shown on rectangular co-ordinates with the polar scatter index on a logarithmic scale. The curves have been plotted on the observed points without fairing, including the irregularities as found. Many of these are doubtless due to experimental errors; but since it can be shown theoretically that in some circumstances such features may occur on the distribution curves, they have not been faired out.

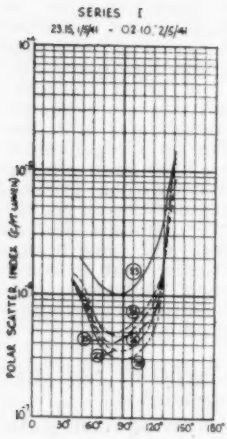
(b) *Scattering Coefficient and Air-Ground Transmission.*

In Fig. 12 the scattering coefficients calculated from the polar scatter have been plotted as a function of altitude for the various ascents. It will be seen that the results all refer to atmospheres which would be classed as having "Moderate" to "Excellent Visibility" (see Fig. 2), and that some in Series III. show extremely low scatter, in some cases owing to the lower air density, less than that due to pure air (Rayleigh scattering) at ground level. It is interesting that it was possible to measure the polar scatter in such extremely clear air—corresponding to a meteorological visibility range of 300 km.—from an aeroplane at 30,000 ft. Fig. 12 also shows the transmission, air-ground, from various heights from each ascent, calculated from the scattering coefficients.

(c) *Other Results from Series I.*

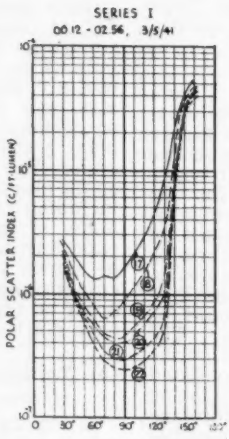
(i) *Telephotometer Measurements.*

These were extremely difficult to make accurately, and a complete series was obtained on one occasion only. They can act as a check only if the atmosphere does not absorb and if it does not change during the period of the observations. It must be remembered that the nephelometer observations covered a piece of the atmosphere about 20 miles long and three and a half miles high; the telephotometer and searchlight observations were confined to a column in the middle of this region. The telephoto-



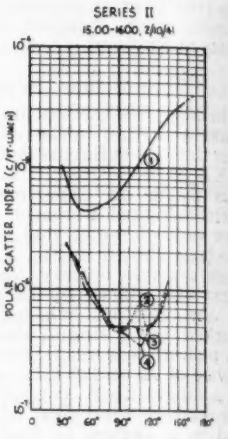
(a)

Curve	Altitude	σ
23...	0	...7.7×10^{-5}/ft.
24...	2,000 ft.	...3.3_3 ,,
25...	4,000 ft.	...4.1_6 ,,
26...	7,000 ft.	...5.5_1 ,,
27...	12,000 ft.	...5.5_2 ,,
28...	18,000 ft.	...5.3_7 ,,



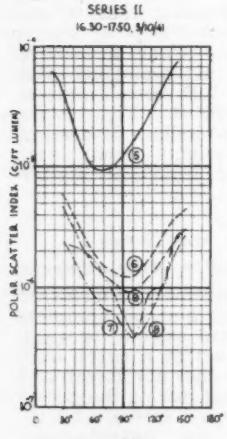
(b)

Curve	Altitude	σ
17...	0	...9.28×10^{-5}/ft.
18...	2,000 ft.	...7.0 ,,
19...	4,000 ft.	...5.7_5 ,,
20...	7,000 ft.	...5.0_5 ,,
21...	12,000 ft.	...4.8_6 ,,
22...	18,000 ft.	...4.4_4 ,,



(c)

Curve	Altitude	σ
1...	0	...15×10^{-5}/ft.
2...	18,000 ft.	...1.4_7 ,,
3...	23,000 ft.	...1.4_8 ,,
4...	29,200 ft.	...1.4_0 ,,

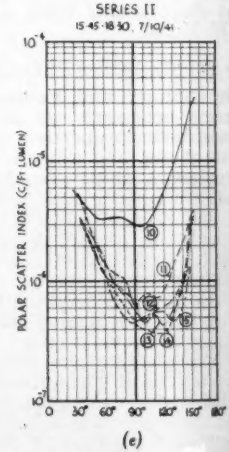


(d)

Curve	Altitude	σ
5...	0	...34.3×10^{-5}/ft.
6...	5,000 ft.	... 3.3 ,,
7...	18,000 ft.	... 1.5_3 ,,
8...	23,000 ft.	... 1.7_5 ,,
9...	29,000 ft.	... 2.5_3 ,,

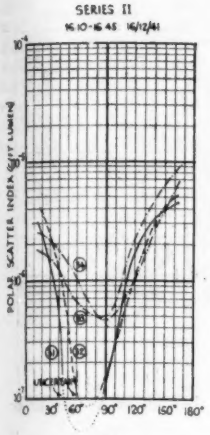
Fig. 11.

Polar distributions obtained in clean air.



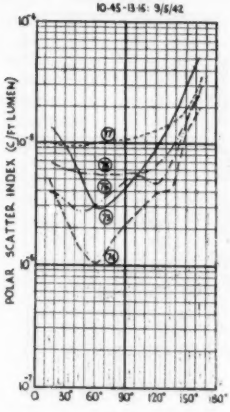
(e)

Curve	Altitude	σ
10...	0	...10.5×10^{-5}/ft.
11...	4,000 ft.	...2.8_4 ,,
12...	7,000 ft.	...2.1_8 ,,
13...	12,000 ft.	...2.1_9 ,,
14...	18,000 ft.	...1.7_0 ,,
15...	23,000 ft.	...1.7_8 ,,



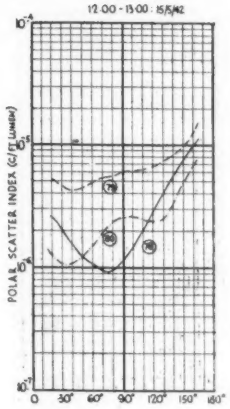
(f)

Curve	Altitude	σ
31	27,000 ft.	$1.4_8 \times 10^{-5}$/ft.
32	23,000 ft.	1.6_7 ,,
33	18,000 ft.	2.4_6 ,,
34	12,000 ft.	1.9_1 ,,



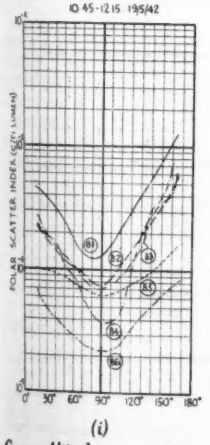
(g)

Curve	Altitude	σ
73	0	12.5×10^{-5}/ft.
74	8,000 ft.	4.7 ,,
75	15,000 ft.	9.4 ,,
76	23,000 ft.	7.6 ,,
77	30,000 ft.	16.0 ,,



(h)

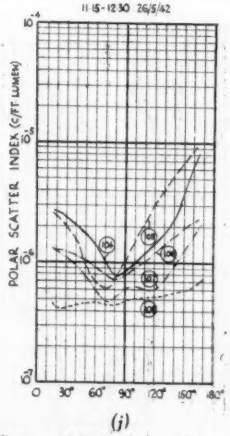
Curve	Altitude	σ
78	0	3.2×10^{-5}/ft.
79	23,000 ft.	8.0 ,,
80	30,000 ft.	3.1 ,,



(i)

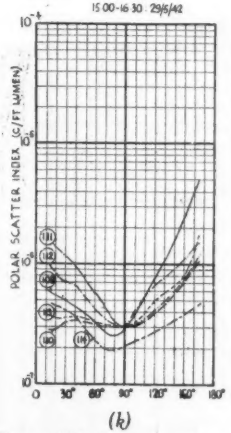
Curve	Altitude	σ
81	0	3.9×10^{-5}/ft.
82	8,000*ft.	1.9_6 ,,
83	8,000†ft.	2.1_6 ,,
84	15,000 ft.	1.7_8 ,,
85	23,000 ft.	1.0_4 ,,
86	30,000 ft.	0.4_6 ,,

*Ascent. †Descent.



(j)

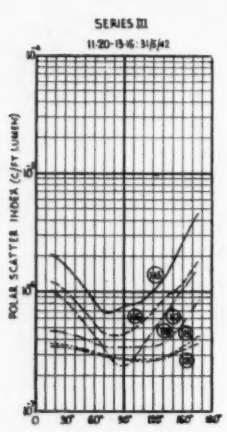
Curve	Altitude	σ
104	0	2.3×10^{-5}/ft.
105	8,000 ft.	3.0 ,,
106	15,000 ft.	1.4_5 ,,
107	23,000 ft.	1.0 ,,
108	30,000 ft.	0.6_4 ,,



(k)

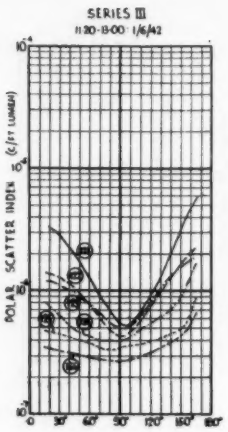
Curve	Altitude	σ
109	0	1.0×10^{-5}/ft.
110	8,000 ft.	0.5 ,,
111	15,000*ft.	0.8_8 ,,
112	15,000†ft.	0.6_2 ,,
113	23,000 ft.	0.6_0 ,,
114	28,000 ft.	0.3_9 ,,

*Ascent. †Descent.



(l)

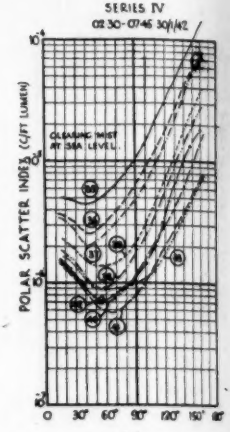
Curve	Altitude	σ
115...	0	...$1.5_6 \times 10^{-5}$/ft.
116...	8,000 ft.	...0.9_1 ,,
117...	15,000 ft.	...0.7_0 ,,
118...	23,000 ft.	...0.5_0 ,,
119...	28,000 ft.	...0.3_9 ,,
120...	30,000 ft.	...0.3_6 ,,



(m)

Curve	Altitude	σ
121...	0	...1.95×10^{-5}/ft.
122...	8,000 ft.*	...1.1_4 ,,
123...	8,000 ft.†	...1.10 ,,
124...	15,000 ft.	...0.71 ,,
125...	23,000 ft.	...0.5_2 ,,
126...	30,000 ft.	...0.4_1 ,,

*Ascent. †Descent.



(n)

Curve	Time	σ
35 ...	02.30 ...	32.5×10^{-5}/ft.
36 ...	03.05 ...	18.4 ,,
37 ...	03.35 ...	15.7 ,,
38 ...	04.05 ...	6.2_5 ,,
39 ...	04.30 ...	8.4_5 ,,
40 ...	05.00 ...	3.5 ,,
41 ...	06.25 ...	2.2 ,,
42 ...	07.05 ...	4.6 ,,
43 ...	07.40 ...	2.2 ,,

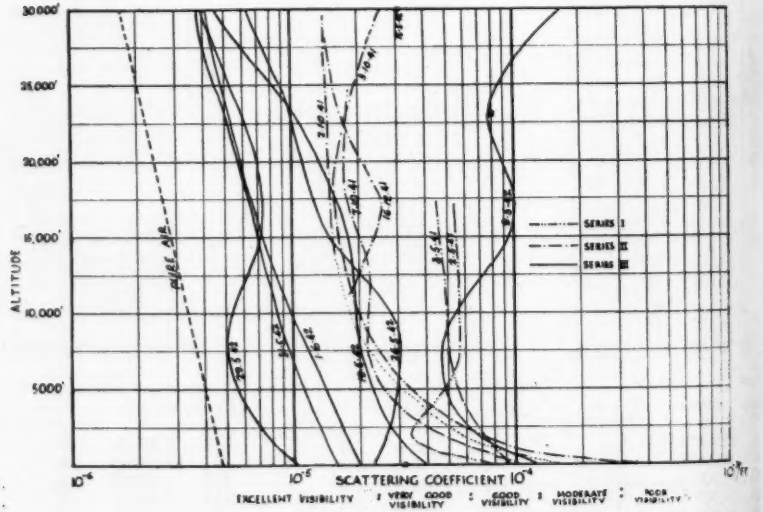


Fig. 12 (a). Variation of scattering coefficient with height.

meter procedure adopted on this early trial did not include many precautions which later experience dictated; some could not be taken for practical reasons. It was not altogether surprising that the results when plotted and extrapolated to zero altitude indicated a transmission of 140 per cent. instead of 100 per cent. The cause of this obvious error was never found; and the best that could be done was to reduce the observations by a factor of 1.4. When this was done, however, it was found that the plotted points lay about the curve calculated from the nephelometer observations, as shown in Fig. 13. This result, while not entirely satisfactory, was felt to be encouraging, as giving no indication of either the presence of absorption or of serious systematic error in the nephelometry.

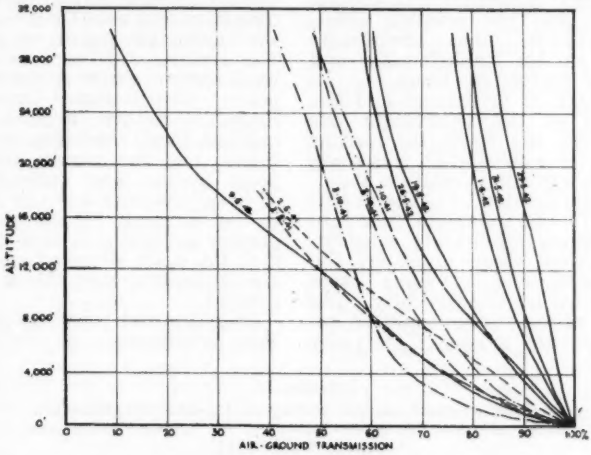


Fig. 12 (b). Variation of air-ground transmission with altitude (clean air).

(ii.) *Searchlight Beam Brightness.*—The searchlight beam brightness can be calculated from the known photometry of the searchlight and from the nephelometer results. This was done for the two currents for the conditions of the second night's observations, and the calculated brightnesses plotted against the observed curve. The results are shown in Fig. 14. The agreement is close, except at the

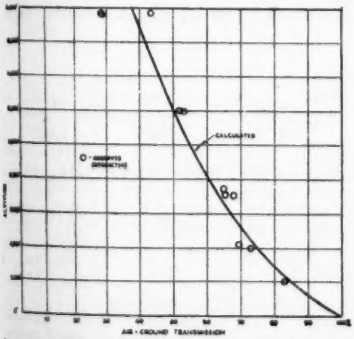


Fig. 13. Observed and calculated air-ground transmission. (Series I, 3/5/41).

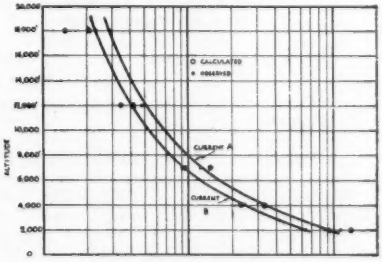


Fig. 14. Observed and calculated brightness of a searchlight beam at 90° to axis. (Series I, 3/5/41)

Note.—Brightness values and particulars of searchlight omitted for reasons of security.

two ends where the calculated and observed results differ by a factor of about 1.5. This agreement can be regarded as satisfactory, bearing in mind the nature of experiments, and the fact that the data for the calculation was the performance of a similar but not identical searchlight lamp and carbons measured in another laboratory, and the possible differences between the atmosphere measured by the nephelometer and that at the searchlight beam.

The values of brightness and the particulars of the searchlight are omitted from the figure for reasons of security; the calculation was made in absolute and not in relative units.

(iii.) *Russell's Method.*—The results by Russell's method were found to give scattering coefficients considerably less than those given by the nephelometer, and in some cases differing from it systematically. The behaviour of the results could be explained from the shapes of the polar distributions. The method is valid only if the polar distribution is identical at all altitudes and when the calibration is made, otherwise an error is introduced. The results on this series, and more markedly those from later series, show that the shape of the polar distribution is far from constant, and generally differs at altitude from that near the ground, where the calibration has to be performed. The greatest difference occurs in the back scatter, which is the part of the polar distribution upon which Russell's method depends. In its original form, therefore, it is not reliable; but the results obtained of polar scatter have enabled variants of it (which cannot yet be described) to be devised, which show much greater promise. It will be realised that the polar distribution of scatter was unknown when this method was devised.

(iv.) *Sky and other Brightnesses.*—The brightnesses of the sky and

Table II.

Various Measurements of Sky and other Brightnesses.

(*Micro-equivalent foot-candles : corrected for Perspex Transmission.*)

April 28–29, 1941.

	2,000′	4,000′	6,000′	8,000′	10,000′	12,000′	15,000′
Ascending							
Sky behind S/L	64–71	71	57	36	108		108
Zenith	43	43	50	43	50		36
Brightest Azimuth	141	825	705	825	1760		1050
Descending							
Sky behind S/L ...			92	92	86	71	
Zenith				71	50	64	

N.B.—(1) Readings of Sky Brightness behind Searchlight Beam were taken at haphazard azimuths and therefore vary.

(2) Readings of Brightest Azimuth were found to be on Aurora Borealis, which was growing brighter.

Table III.

May 1–2, 1941.

Altitude	18,000′		12,000′		7,000′		4,000′		2,000′	
Time*	2315	2335	2350	0005	0025	0035	0050	0100	0110	0125
†Sky behind S/L	142	320	283	212	141	141	107	71	78	57
Zenith	33	42	64	47	50	50	50	35	43	35
Ground		34			12		7.8		5	
Illum. normal to Moon ...		580								
Notes ...			Distant haze top apparently 8,500				Moon entering haze 0105			

*Clock time = 1 hour in advance of G.M.T.

†*N.B.*—Readings of Sky behind Searchlight taken in darker part of Sky.

ground on three flights are shown in Tables II, III, and IV.

(v) *Psychrometer Readings.* — The readings of the psychrometer are given in Table V.

These are in agreement with those obtained from the meteorological flights made in the vicinity before and after the tests. The Meteorological Office report on the weather conditions is given in Appendix I.

V. Measurements Made in Industrial Hazes

While the high-altitude investigation was in progress, a request was made for information on the properties of industrial atmospheres such as occur in the vicinity of manufacturing towns, where much smoke is present at any rate in the lower levels. It was expected that the main difference between such atmospheres and the clean atmospheres hitherto investigated would lie in the presence of absorption as distinct from, and in addition to, attenuation due to scatter. It was felt that it might be possible to determine the absorption by a method similar to that used in the first series of high altitude flights if the technique were improved: i.e., by making a series of nephelometer observations at various altitudes concurrently with air-ground transmission measurements. The attenuation from air to ground due to scatter alone can be calculated from the nephelometer observations; if the measured transmissions are systematically lower than the calculated values, the presence of absorption is inferred.

The experimental conditions differ from those previously discussed in that observations must be made at low altitudes and over a restricted region. This makes the use of aircraft impossible, since—quite apart from considerations of safety—the aircraft would pass through the region far too quickly, and the apparent angular speed of the ground would make telephotometer observations of the target extremely difficult. It was possible, through Mr. Good and by the collaboration of R. and E. Department, Ministry of Home Security, to obtain the use of an ob-

Table IV.
May 2–3, 1941.

Altitude	18,000′		12,000′		7,000′		4,000′		2,000′	
Time*	0012	0033	0045	0100	0115	0132	0140	0155	0207	0225
†Sky behind S/L	350	405	350	283	263	162	263	106	56	56
Zenith	71	64	64							
Ground	32		21		14		4.4		6.2	
Sky nr. Moon ...		1040								
Opp. Moon ...		174								
90° to Moon ...		197								
Illum. normal to Moon ...		580								
Notes ...					Traces of Cloud.		Haze just below 4,000′ Moonset.		Ground Haze lit by S/L.	

*Clock time = 1 hour in advance of G.M.T.
†*N.B.*—Readings of Sky behind Searchlight taken in darker part of Sky.

Table V.
Psychrometer Readings.

	18,000′	12,000′	7,000′	4,000′	2,000′
May 1–2, 1941					
Dry bulb	−1°F.	17°F.	28°F.	39°F.	48°F.
Wet bulb	−3	15	24	34	41
May 2–3, 1941					
Dry bulb	−2	15	28	39	45
Wet bulb	−3	14	26	35	40

servation balloon situated in an industrial region, which seemed ideal for the purpose; and a series of observations was successfully made from it on a number of occasions and in two different localities at heights up to 3,000 ft.

(1) Installation of Apparatus in Balloon Car, etc.

(a) *Nephelometer.*

The latest version of the nephelometer, illustrated in the photograph of Fig. 3, was used. It was fixed to a board carried on two stout steel brackets, by which it could be clipped over the side of the balloon car, projecting clear of the interior, so as not to obstruct the occupants. (There was just—and only just—room for two men, the observer and the pilot, in the car.) The apparatus was put on to the car at the last moment before taking off, thus avoiding the chance of damage to it while the balloon was being handled in the dark; this scheme also facilitated the taking of ground observations with the apparatus well out of the way of the rigging and crew. The photograph of Fig. 3 shows the nephelometer as it was used in the balloon. The black screen on the right intercepted the main beam for security reasons. The board also carried the main resistance, voltmeter, calibrating bar (in a clip, and secured with a safety lanyard), writing pad and pencil, and two screwdrivers; a small brass fiddle was also arranged to prevent any small objects from falling into space. The whole of the apparatus was arranged so that in an emergency it could be jettisoned, in order to let the observer get out of the basket; the car suspensions prevented exit from the sides. The battery, a single 12-volt 36 amp.-hrs. aircraft battery, was placed on the floor of the car and took the place of one of the ballast bags.

(b) *Telephotometer.*

In this experiment the telephotometry was much easier than in the aircraft, for there was no vibration to contend with, and the target was of much larger subtense and was stationary. It was therefore possible for the observer to use the telephotometer simply held in his hand, and to take his time over the observations. The control box was carried on the board with the nephelometer, and the instrument was run from a tapping on the main battery; when not in use, it was hung on a hook on the edge of the board.

Fig. 15 shows the apparatus in position on the car, and Fig. 16 shows the observer using the nephelometer.

(c) *Targets.*

The ground target has already been described. In the earlier experiments it consisted of the white sheet laid on the ground on a tarpaulin, but this gave trouble both in the non-uniformity of brightness of the sheet, which made the measurement of its brightness from the ground difficult, but also because frost or dew formed on the sheet and changed its reflection factor. The form finally used was that

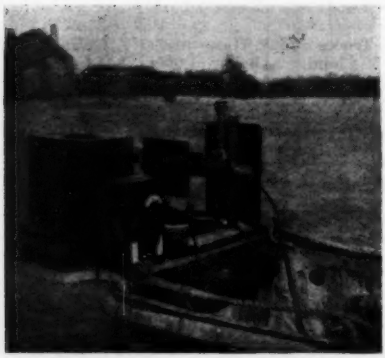


Fig. 15. Apparatus in balloon car.

Fig. 16. Observer in balloon car.

described above and illustrated in the photograph, Fig. 17. This acted very well, was easy to erect, and gave a very nearly uniform brightness which remained constant and was easy to check.

For the measurement of the transmission at ground level, the hemisphere target described above was used mounted in the back of a small van and run from the van battery with resistance and voltmeter control. The telephotometer was taken to a distant point about 900 ft. away; for the near reading the telephotometer was again used close to the target. Fig. 18 shows the sphere target, and the nephelometer in use on the left.

(2). PROCEDURE.

As these experiments proceeded, it became obvious that the crux of the work was the telephotometry. A study of Fig. 2 will indicate the reasons. The heights involved were much smaller than before, so that transmissions were higher; and the whole work depended upon the difference between the measured and the calculated values. A single small error in an observed point could make the curves meaningless. The telephotometry had therefore to be carried out with the greatest possible care and accuracy.

It was inconvenient to employ control on the lamps lighting the white sheet, and even if this had been used, it would have been necessary to check that its reflectivity had not changed due to frost or damp. In the latest series of tests, therefore, the brightness of the sheet was measured by another observer with a second photometer at nine points over its surface simultaneously with each series of readings from the balloon. The balloon observer took at least six readings from each height. Before and after the run, simultaneous readings were taken on the sheet with both instruments, as an intercheck. The ground observations on the sheet were taken from a high step-ladder. (Fig. 17.)

The test programme for each run was therefore as follows:—

1. Set up nephelometer on ground and make ground observation.
2. Telephotometry of sphere target over 915 ft. range, concurrently with 1.
3. Measurement of brightness of white sheet with both photometers from step-ladder, air observer using the telephotometer. (Intercheck of instruments.)
   (While these observations were being made, the balloon crew were getting the balloon off its bed and preparing the car.)
4. Air observer dressed; apparatus transferred to car. Balloon ascended to first level.
5. Nephelometer observations from car.
6. White sheet illuminated; simultaneous observations by telephotometer from balloon and by illuminometer from step ladder. Extinguish white sheet.
   (5 and 6 repeated at each level.)
7. Balloon hauled down; apparatus re-

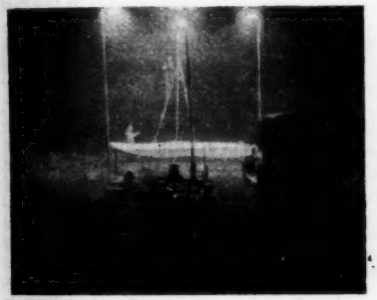


Fig. 17. Telephotometer sheet target.

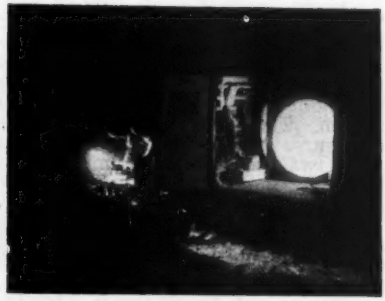


Fig. 18. Telephotometer hemisphere target and ground nephelometry.

moved to ground station; observer undressed.
8. Simultaneous measurements on white sheet with telephotometer and illuminometer. (Intercheck of instruments.)
9. Nephelometry on ground.
10. Telephotometry of sphere target over 915 ft. range (concurrently with 9.)

The whole series of operations occupied about three hours. The air observations were taken mostly by Mr. J. W. Morse, and the ground observations by Mr. S. S. Beggs, Mr. Morse, Mr. G. K. Monks, and the writer.

(3) Conditions of Observation.

(a) *Personal.*

The conditions of observation were much less arduous in the balloon car than in the aircraft. The main advantage was the absence of vibration, noise and movement; this balloon was quite steady in wind though it "weaved" slowly from side to side. The observer could take his time, and he was not troubled with the interlocking of many experiments as in the first series. He wore no face mask or telephones and had no leads attached to him. The ground organisation was of course very much simpler, and there was telephone communication between the ground and the air observers.

The main difficulties in observing from the car are cold and wind. The observer is unprotected, and there is almost always wind at 1,000-3,000 ft., sometimes up to 40 m.p.h. An incidental trouble with wind is that it makes the observer's eyes water, which makes photometry difficult. The observers are also very cramped for space in the car. It just holds two men, and it was possible for the observer to sit only with difficulty, on the floor, when not observing. The apparatus projected out from the end of the car, and the car suspensions were so placed that the photometer was not easy to reach near 160 deg. But those discomforts were not sufficient to affect the accuracy of the observations, which was considerably greater than was possible in the aeroplane.

(b) *Operational.*

The conditions under which it was possible to fly the balloon were different from those which limited aeroplane flights. The aeroplane could only be flown in good visibility, and generally only when there was little cloud; wind was no disadvantage. The balloon, on the other hand, could not be flown when there was either much wind or risk of lightning; but the visibility was unimportant. Thus both series of experiments are limited and not fully representative, but being limited in different ways they are not strictly comparable with one another. The observations on industrial atmospheres were made on the whole in much thicker conditions than those on clean air.

(4) Results.

Observations were made in the vicinity of two industrial towns, engaged mainly in light industries. (The precise localities may not yet be disclosed.) Three ascents were made at the first site: at the second two series of experiments were made; in the first five ascents were made and two series of ground readings; in the second, three ascents were made. There were several interruptions to the work, by air raid alerts, deteriorating weather, and for operational reasons; and from all the observations there were two complete series at the first site and four at the second. The technique of the observations was continually improved during the series; the full technique described above was not used until the final series. The results are shown in Figs. 19 (a—f); the details of the experiments are given in Table VI.

VI. Discussion of Results

The results generally indicate that it has been possible to make measurements of the photometric properties of the atmosphere from aircraft and balloons with sufficient precision for the results to be significant and to check one another where such checks have been possible. The nephelometer has shown itself to be a sensitive means of determining the scatter of the atmosphere, and has given little trouble in the hands of skilled operators. Measurements of atmospheric transmission, in the conditions of these experiments, has taxed the patience and ingenuity of the experimenters and is very difficult to make

reliably, even under good conditions; but it can be done, sufficiently accurately for the rather stringent requirements of the determination of absorption.

(1) Polar Scatter Index.

(a) *Clean Air.*

The shapes of the polar distributions show great variations, from distributions which are almost uniform with those which show changes of 100:1 in polar scatter index with angle. In some cases the curve shows no minimum at all, increasing steadily from 0 deg. (back scatter) to 180 degs. (forward scatter); in other cases there is a very pronounced minimum. In nearly all, however, there is a minimum which occurs at from 60 degs. to

Table VI.

Locality I.

1st Series.

No. and Fig. No.	Date	Max. Alt.	Results	Notes on Experiment	Weather
I 19a	10/3/42	2,500′	α 20–60 × 10^{-5} σ 10–15 ,,	First Experiment; ground transmission not taken.	Definitely misty; haze top just above 2,500 ft. Light E. wind, bringing smoke from town.
II 19b	29/3/42 (Sunday)	2,500′	α negligible σ 10–50 × 10^{-5}	Ground transmission measured.	Slight W. wind; balloon to windward of factories.
			Locality II. 2nd Series.		
III 19c	16/8/42 (Sunday)	2,000′	α up to 45 × 10^{-5} σ 1 to 12 ,, Results uncertain; probably two absorbing layers.	Tests interrupted by raid warning; during which reflection factor of sheet altered by frost. Ground telephotometer range too short.	Wind at ground 0 m. p. h., increasing to 35 m. p. h. at 2,000 ft. Haze noticeable 0-500 ft., ground features indistinct and grey. Above 500 ft. haze appeared to clear and ground appeared darker
IV 19d	18/8/42	1,000′	α 40–100 × 10^{-5} σ 3–4 ,, Absorbing layer 0–250 ft.; little above to 1,000 ft.	High wind limited maximum altitude.	High wind reaching 50 m.p.h. at 1,000 ft. Appeared very clear night; no haze visible (few factories to S. of site). Ci. cloud with large gaps.

(Continued on next page)

Table VI. *(continued).*
3rd Series.

No. and Fig. No.	Date	Max. Alt.	Results	Notes on Experiment	Weather
V 19e	7/10/42	2,000′	α 10–20 × 10^{-5} σ 4–25 „ Two absorbing layers, 0–250 ft. and 1,300 ft. and above.	Final procedure adopted; ground telephotometer range 915 ft. Target suspended. Results consistent.	Cloudy; obvious haze by day. Broken cloud at night and cloud base lowered after dark. Slight S.W. wind on ground; 20 m.p.h. at 750 ft. Haze top noted 600 ft.; slight rain at end of test.
VI 19f	13/10/42	2,000′	α 10–20 × 10^{-5} σ 4–15 „ (Earlier, $\sigma = 245 \times 10^{-5}$/ft. Absorption from ground to 1,400 ft.	Very heavy ground haze cleared during tests; early haze neglected. Trouble with electrical circuit in later rdgs. curtailed some curves.	Very hazy at first; wind nil. Cleared after 250 ft. rdg. had been taken; apparently no change above.

Table VI gives the details of the completed tests. There were, in addition, some other results, obtained in incomplete tests, which are recorded in Table VIa below. They were all obtained at the second locality.

90 degs,, or sometimes a little more. It was thought at first that the distributions fell into two types, one having little back scatter and a shallow minimum at about 60 degs. (this distribution is similar to that reported by Rocard and Hulbert, and has been referred to as the "Rocard type"); the other having back scatter comparable with the forward scatter and a pronounced minimum near to 90 degs. But the whole series of results shows curves at all stages between these two types, and it is scarcely possible to generalise.

It has been noticed, however, both in the results here reported and also in an extended series of observations by H.M.S. Vernon that the distribution at ground level generally tends to be of the "Rocard" type; Fig. 11n is characteristic. This shows a series of curves taken in a clearing mist over the sea and at sea level. In very clear conditions at ground level the minimum tends to become more pronounced and to occur at greater angles, and the back scatter increases relatively; in thicker conditions the converse is often true. This conclusion is not however rigid.

There seems to be no correlation between the shape of the distribution and height, and little with its amount. In many cases the scatter is greater near the ground than at greater altitudes, as is to be expected; and the scatter near the ground is often more variable with time. As Fig 12a shows, the curves of scattering co-efficients as a function of altitude tend to slope backward, indicating a reduction of scatter with height; but they do not always do so. There is evidence of stratification in some cases, but in the clean air measurements there are insufficient points to determine it with accuracy. On one interesting occasion (9.5.42) the scatter fell for the first 7,000 ft. and then increased again, and was greater at 30,000 ft. than it was at the ground. The polar distribution was however very different at 30,000 ft. from that at the ground.

A consideration of the curves shows that in most cases the polar scatter index, for a given scattering coeffi-

Table VIa.

2ND SERIES.

No.	Date	Max. Alt.	Results	Notes on Experiment	Weather
VII	14/8/42	1,000 ft.	α 15 × 10^{-5} σ 7 — 11 „ Absorption Coeff. at grd. level; uncertain.	Stopped by cloud at 1,000 ft. Atmos. varying; telephotometry inaccurate.	Cloud at 1,000 ft.
VIII	17/8/42	500 ft.	α 22 × 10^{-5} σ 7 — 18 „ Absorption in very thin layer near ground; none found from air results.	Tests interrupted by raid warning; no check readings possible. Those taken seem consistent. Improved check of sheet brightness.	Wind W. No cloud: appeared to be much haze about; looked misty at 250 ft., but less apparent at 500 ft. Smoke could be smelt at 500 ft.
IX	23/8/42 (Sunday)	0	α 14·7 × 10^{-5} σ 20·3 „	Ground observations only. Telephotometry conditions improved; range now 800 ft. Results more certain.	Slight N. wind; slight rain during nephelometer readings.
X	24/8/42	0	α 4·5 × 10^{-5} σ 4·5 „	Ground observations only. Attempt to measure smoke screen; failed as smoke did not reach site.	Fresh S.-S.E. wind slight till 11 p.m., when wind veered S.-S.W. and freshened, becoming strong above 1,000 ft. Readings began about 11 p.m.
			3RD SERIES		
XI	11/10/42	250 ft.	α 0 σ 62—134 × 10^{-5} No absorption on ground or up to 250 ft.	Test interrupted at 250 ft. by Balloon Control. Readings consistent.	Very hazy near ground, but clear above. Wind nil or slight W. on ground. Haze seemed to clear slightly between time of taking ground readings and taking off. Cone of searchlights scarcely visible in lower parts.

cient, is fairly constant in the region of 150 deg., but is very much more variable at the tail of the curve representing back scatter. This is simply because in most curves the forward scatter is much greater; consequently the flux in a (say) 5-deg. zone is a maximum near 150 deg. The total flux represented by the polar distribution, and consequently the

Curve	*Altitude*	σ
87 ...	0 ...	117×10^{-5}/ft.
88 ...	250 ft. ...	18.5 ,,
89 ...	500 ft. ...	7.5 ,,
90 ...	1,000 ft. ...	13.7 ,,
91 ...	2,000 ft. ...	13.9 ,,
92 ...	2,500 ft. ...	22 ,,

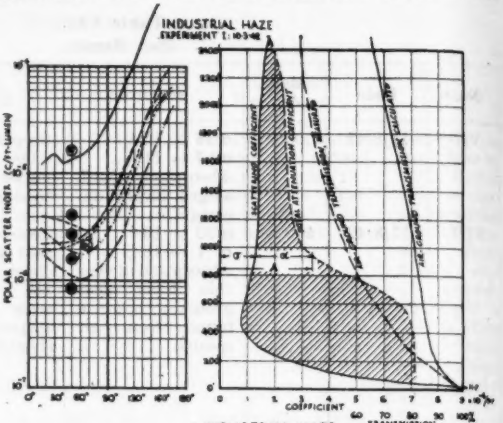


Fig. 19a. Results in industrial haze. (Week night to leeward of town.)

Curve	*Altitude*	σ
93 ...	0 ...	51×10^{-5}/ft.
94 ...	250 ft. ...	15.5 ,,
95 ...	500 ft. ...	15.7 ,,
96 ...	1,000 ft. ...	19.5 ,,
97 ...	2,000 ft. ...	10.6 ,,
98 ...	2,500 ft. ...	14.1 ,,
99 ...	0 ...	23.5 ,,

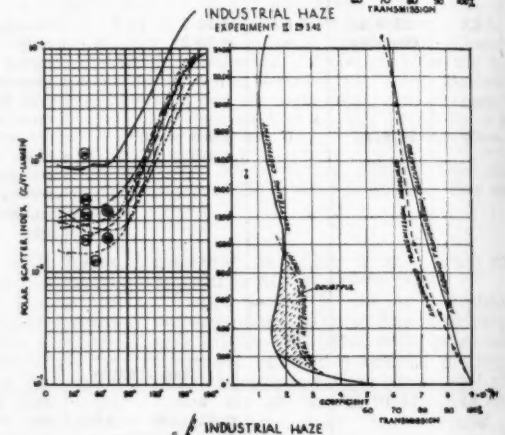


Fig. 19b. Results in industrial haze. (Sunday night to windward of town.)

Curve	*Altitude*	σ
133 ...	0 ...	32.3×10^{-5}/ft.
134 ...	250 ft. ...	38 ,,
	Interrupted	
135 ...	0 ...	11.5 ,,
136 ...	250 ft. ...	12.3 ,,
137 ...	500 ft. ...	5.7_5 ,,
138 ...	1,000 ft. ...	1.8_6 ,,
139 ...	1,500 ft. ...	0.8 ,,
140 ...	2,000 ft. ...	0.7_6 ,,

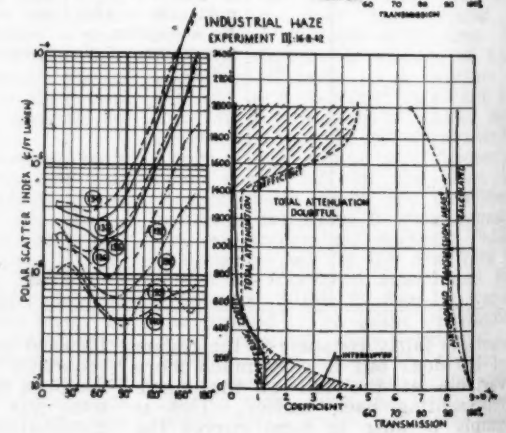


Fig. 19c. Results in industria haze.

Curve	Altitude	σ
144	0 (start)	$3.7_2 \times 10^{-5}$/ft.
145	0 (finish)	5.0 ,,
146	250 ft.	3.2_8 ,,
147	500 ft.	4.0_5 ,,
148	1,000 ft.	3.3_2 ,,

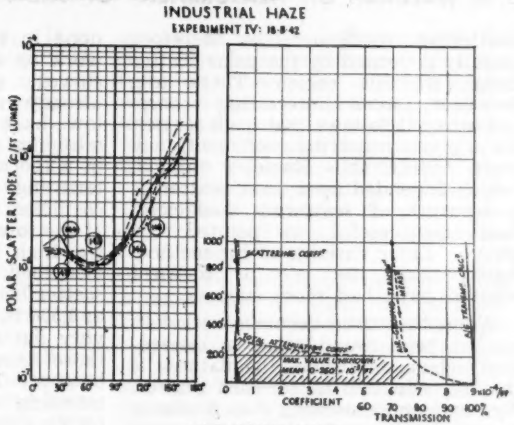


Fig. 19d. Results in industrial haze.

Curve	Altitude	σ
154	0(start)	24×10^{-5}/ft.
155	0(finish)	32.1 ,,
156	250 ft.	19.9 ,,
157	500 ft.	14.1 ,,
158	750 ft.	8.8_5 ,,
159	1,000 ft.	4.3_8 ,,
160	1,500 ft.	4.3_8 ,,
161	2,000 ft.	7.5 ,,

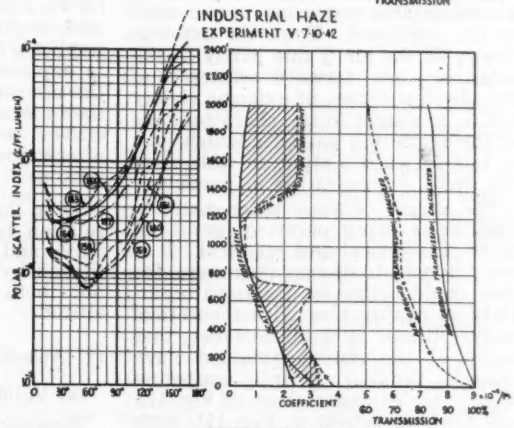


Fig. 19e. Results in industrial haze.

Curve	Altitude	σ
165	0(start)	245×10^{-5}/ft.
166	0(finish	16 ,,
167	200 ft.	29 ,,
168	500 ft.	3.7 ,,
	(ascent)	
169	500 ft.	4.5_8 ,,
	(descent)	
170	1,000 ft.	4.5_6 ,,
171	1,500 ft.	7.2 ,,
172	2,000 ft.	7.9 ,,

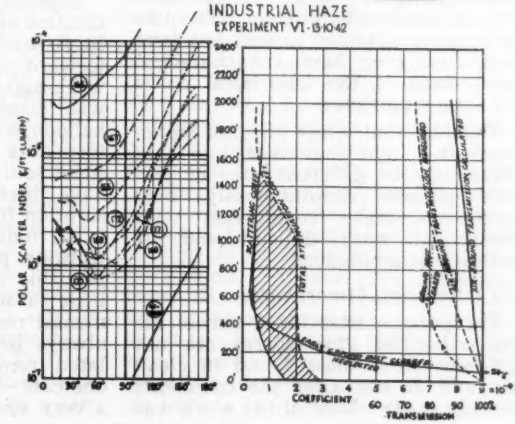


Fig. 19f. Results in industrial haze.

scattering coefficient, is therefore usually governed by the polar scatter index in this region. There are, however, some interesting consequences. It follows that back scatter, for a given scattering coefficient, may vary widely; thus Russell's method, which depended upon back scatter as a measure of scattering coefficient, was unsuccessful, as pointed out above. Later variants of his method, based upon the use of forward scatter, have had more success.

When the curve becomes very flat, as has been found often in exceedingly clear conditions, the flatness is due to reduction in forward scatter. By the same reasoning this produces a considerable reduction in the scattering coefficient. Thus, the extreme clarity of the air is due partly to the relatively low forward scatter; and the physical causes of extreme clarity are to be sought in the characteristics of the scattering particles which lead to low forward scatter, as well as to the small concentration of particles.

The shapes of these polar distributions raise many points of great interest, theoretical and practical. It is not proposed to discuss them here, for they could better be discussed separately in conjunction with theoretical work. It can be said, however, that many of the curves obtained have shapes familiar from scattering theory; for example, those of Fig. 11n and the two lowest in Fig. 11f, with very pronounced minima. The two latter were obtained in very low temperatures; they have the characteristic shape of the theoretical curve for larger particles.

The fact that white and not monochromatic light was used, and that there may be different sizes of particle present simultaneously, may sometimes make comparison with theoretical work difficult and its indications ambiguous.

(b) *Industrial Atmospheres.*

The polar scatter index curves for the industrial atmospheres are not different from those found in clean air, and do not alter the comments already made. Most of the work was done in thicker conditions than the work on clean air, and most of the curves show the characteristic, already noted, of high forward and low back scatter, with a shallow minimum at about 60 deg. The results in Experiment III (Fig. 19c) are interesting. A long range of scattering coefficients occurred; the polar curves at the lower levels, where the scatter was high, have the characteristics just described; but at 1,000 ft. the back scatter becomes more prominent, and at 1,500 ft. the scatter is very low and very flat curves occurred similar to those found previously at very great heights. The curve at 1,500 ft. is interesting as showing a decrease in forward scatter with increase in angle, with a maximum at 125 deg., which implies a 55 deg. halo. This is difficult to explain as an experimental error; the unusual readings were noticed at the time and repeated, and more usual curves were obtained immediately afterwards; the curve is believed to be genuine.

Thus there seems to be some correlation between the shape of the curve and the scattering coefficient—though by no means a close one—but not between the shape and the altitude.

(2) Absorption Coefficients

(a) *Validity of the Method.*

Experiments I and II give an indication of the validity of the method. In Experiment I the balloon was to leeward of the factory area on a week-night, and heavy absorption was found. In Experiment II., the balloon was to windward of the factory area on a Sunday night, when some sources of pollution may not have been operating; and the absorption found was insignificant. This is an indication that the method is working properly, and that in the probable absence of smoke it shows little or no absorption. The experimental results for transmission have always been less than those calculated from the scatter, and, except in one case—Experiment II (and then to a very small degree)—have never in-

dicated a negative absorption. It is difficult to be sure of the validity of an experiment of this kind, but all the indications are that the results are significant. They cannot, however, be regarded as particularly accurate, in view of the difficulty of the experiment; and the values of absorption coefficient are perhaps best regarded as indicating its order of magnitude. So far as these experiments go, there seems evidence for expecting the atmosphere to behave as clean air except in the *immediate* vicinity of industrial pollution. In Experiment II, though the balloon was to windward of the adjacent town, it was almost down wind from a much larger industrial area only about 18 miles away; yet there was no material absorption found. This result seems to conflict with the reports of smoke haze extending for many miles to leeward of an industrial area. But casual observation is not sufficient to detect smoke as distinct from scattering particles; these results seem to indicate only that true absorption due to smoke does not extend far. Industrial atmospheres may well be more hazy, due to greater scatter.

(b) *Amount of Absorption.*

The amount of absorption, when found, has generally been of the order of $10 - 40 \times 10^{-5}$/ft.; and it has generally occurred at altitudes of less than 2,000 ft.—although on two occasions (Experiments V and III) it was found to continue at 2,000 ft. The absorption sometimes occurred in dense layers close to the ground (Experiments I, IV, and V; and apparently in VIII). In several cases it occurred in strata, or it increased above ground level. Stratification of the atmosphere is a well-known phenomenon; this result is not surprising.

The amount of absorption appears to be unrelated to the amount of scatter. Sometimes strong absorption occurred on nights when the scatter was very low, and the atmosphere appeared clear. (Experiment IV.) On other occasions the absorption was negligible, although there was a fair amount of scatter. (Experiment II, XI.) The latter experiment was interesting: there was a slight wind, which would have been expected to bring the smoke; it was very hazy, which tends to mask the smoke effect; but the absorption coefficient was nil, or in any case less than 4×10^{-5}/ft. When smoke has been found, the absorption coefficient was generally 5 - 10 times this value.

This effect would be consistent with a mechanism in which the particles responsible for the scatter and those responsible for the absorption are different and behave independently; probably they are of different sizes—though these experiments do not indicate the sizes of the absorbing particles.

(3) Scattering Coefficients.

The amount of scatter varied considerably. It was often found that the scattering coefficient fell rapidly on leaving the ground, indicating a ground mist. Above the ground layer conditions were often clearer and more constant. On the night of October 13 the initial ground mist showed a scattering coefficient of 2.5×10^{-3}/ft. ("Fog," with a daylight visibility range of 1,000 yards) clearing at 500 ft. to 3×10^{-5} ("Very good visibility" with a daylight visibility range of about 25 miles in the absence of smoke). Later the ground mist was seen to disperse, and the ground mist had a scattering coefficient of 1.6×10^{-4}/ft. ("Moderate visibility" with a daylight range of about 6 miles). The ground layer was seldom more than 500 ft. thick, and sometimes there was a clearest region at about 500 ft. above which it thickened again. A similar effect was found in the high altitude results on a larger scale, on two occasions with a minimum scatter at a few thousand feet. Occasionally the haze at first increased with height above the ground. This was seen in Experiment III., when it occurred in two sets of measurements separated by about two hours, up to 250 ft. On the same occasion the scatter diminished steadily with height above 250 ft., and by 1,500 ft. had reached the very low

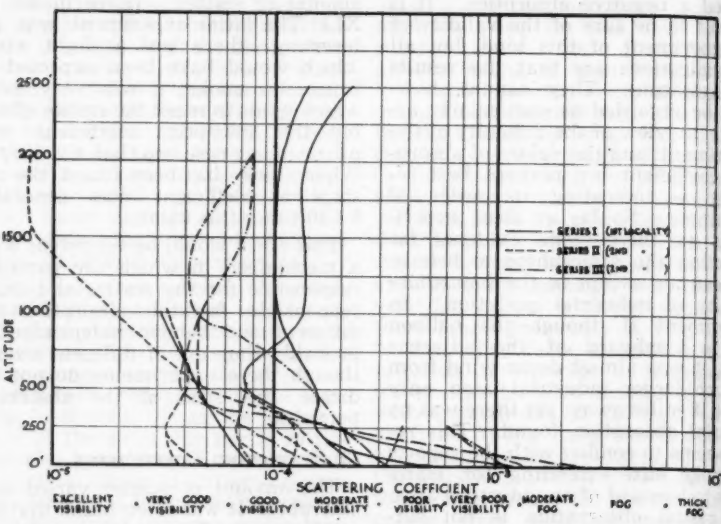


Fig. 20. Variation of scattering coefficient with altitude (industrial haze).

value of 8×10^{-6}/ft., which is only about twice that for pure dry air.

The variation of scattering coefficient with height found in the industrial atmospheres is shown in Fig. 20. This may be compared with Fig. 12 which shows corresponding curves for clean air; but it must be remembered that there is no necessary correlation between the two sets of data; the industrial atmospheres were measured in weather which was on the whole thicker than that when the clean air measurements were made. The height scale in Fig. 20 is ten times, and the scattering coefficient scale is 1/10, that in Fig. 12. It would probably be legitimate for any problem, in default of better information, to use the present results for scatter and absorption to represent conditions over an industrial area for the first 2,000 ft., and thereafter to use those for clean air. The upper ends of the curves in Fig. 20 lie well within the region covered by those in Fig. 12 at 2,000 ft. so that there are no obvious discrepancies.

(4). Air-Ground Transmission.

The air-ground transmission is also shown in Figs. 12b for clean air, and in Figs. 19a-f for the industrial atmospheres; these form an interesting comparison. The transmission air-ground in the industrial atmospheres from 2,000 ft. varied from 40 per cent. to 75 per cent. For most cases it is about 60 per cent. at 2,000 ft. In the clean air, measured in clearer conditions on the whole, the transmission at 2,000 ft. varied from 76 per cent. to 98 per cent. In the haziest conditions measured in clean air a transmission air-ground of 60 per cent. occurred at 8,200 ft.; on the clearest day measured in clean air the transmission from 30,000 ft. was 85 per cent. If the clean air data is used for the upper strata and the industrial air data for the lower, the air-ground transmissions shown in Fig. 12b will be reduced by a factor of about 0.75, by the industrial atmosphere assumed near the ground.

The above discussion of the results obtained is by no means complete. There is doubtless much more to be gained from a detailed study of them; but it must be left for later and probably other workers. The present paper is confined to pointing out such characteristics of the results as may be im-

portant in using them for illumination and visibility problems.

VII. Value of the Results, and suggestions for further work.

In the first section it was pointed out that the results here given were far too limited to be treated as characteristic, or to be related to known meteorological conditions. They are sufficient to indicate at least what has happened on a number of occasions, in autumn-winter, spring and summer; they indicate at least some of the variations which may be encountered. But they are quite insufficient to indicate how frequently or in what circumstances particular conditions may be expected.

In using them for the solutions of problems, several methods have been employed according to the nature of the problem. In some problems the complete data for actual occasions have been taken just as they stood; the whole problem has been calculated for two or three occasions with different atmospheric conditions, in order to see how serious was the effect of changing atmospheric conditions. In other problems, a mathematical expression was used which gave an approximation to a typical curve. In others, again, a hypothetical atmosphere was postulated, the properties of which were built up from the available data, so as to be —so far as could be judged—fairly representative of the conditions of interest. In most problems of visibility it is important to try the effects of changing the atmosphere; otherwise long computations may be made upon some hypothetical set of conditions, and conclusions drawn, without recognising that changes in the atmosphere which are likely to be encountered may entirely alter the performance, visibility, or whatever it may be. In one example worked out it was found that an alteration in the amount of back scatter in the atmosphere might well result in a change from an object seen in silhouette to one seen as a light object on a dark ground; in another case, changes such as have been found in clear, clean air could make variations in the range at which something could be seen, from five miles to nearly 40 miles. It is very important to recognise the probable effects of these changes, for they may alter the whole approach to problems; and thus prevent the waste of much effort in endeavours to do something which in practice will seldom be under control. Such effects may also explain inconsistencies in the results of field visibility experiments, which notoriously refuse to behave as expected.

There are many problems of visibility, particularly visibility from the air, the mathematical solution of which is difficult, and in any case cannot be even commenced without some data such as these. Mathematicians are naturally loth to spend time on long calculations based on assumptions which may be untrue or unrepresentative, and without knowledge of what variations are to be expected. There are many problems of more prosaic peace-time illuminating engineering, in such fields as street lighting and the use of headlights, and in outdoor photometry, where atmospheric effects are important and in which these data will enable progress to be made.

The main interest of atmospheric effects will, however, surely be in connection with air travel. The importance of visibility of the ground from the air is probably less along air routes, where navigation by radio and astronomical methods is straightforward, than the visibility of the ground during the operations of take-off, and particularly of landing. Then the visibility of the ground and of obstruction and runway lights, is of special importance; and it sets a very pretty crop of problems, which can only be solved by a knowledge of the photometric properties of the atmosphere.

In parallel with these problems are those of the meteorologist, who may have to forecast visibility to an increasing extent. The author is not competent to discuss this subject; but on general considerations it would seem clear that the more that is known about what causes good and bad visibility, the better will be the prospects of connecting those causes with other and better understood meteorological phenomena, and in the end the better the chances of making

accurate forecasts. It is here that the hope of being able to estimate the particle size, at least in some cases, from the shape of the polar curve of scatter index, may be of special interest on the more theoretical side.

But we badly need data on a statistical basis. For many problems, little further progress will be possible until regular and systematic observations are made and analysed. This is a big undertaking, particularly in the analysis of the results; but it is hoped that it may be thought worth while. Some tentative designs have been thought out for a polar nephelometer which would be fully automatic and would record photographically, so that it could be taken up on routine meteorological flights; such an instrument might be made to work satisfactorily. The determination of industrial absorption is much less easy, and might not be possible as a routine matter. Other methods have been worked out for measurements in connection with specific problems, which cannot yet be discussed, but which might be pressed into service for the collection of data. It is, however, hoped that it may be found worth while to make some such systematic study of the upper atmosphere, not only with a view to routine collection of data, but also because it may open new and fascinating fields in the investigation of Nature.

References.

The literature on atmospheric scatter is very large; Middleton ("Visibility in Meteorology," Toronto Univ. Press, 2nd edition) gives a fairly complete bibliography. The following references are of particular interest in the work described:—

RAYLEIGH, LORD.—Phil. Mag., 41, p. 447 (1871): Scattering by Small Particles. Proc. Roy. Soc. (A), 84, p. 25 (1910): Incidence of Light upon a Transparent Sphere of Dimensions Small Compared with the Wave-length. Proc. Roy. Soc. (A), 90, p. 219 (1914): Diffusion of Light by Spheres of Small Refractive Index.

RYDE, J. W.—Roy. Soc. (A), Vol. 131, p. 451 (1931): Theory of Scattering by Particles.

GOLD, E.—Q. Jour. Roy. Met. Soc., 65, p. 139 (1939): Expression of Opacity of Atmosphere in "Nebules."

BENNETT, M. G.—Q. Jour. Roy. Met. Soc., 58, p. 259 (1932), and 61, p. 179 (1935): Diffusion of Outline of Distant Objects by Atmospheric Scatter.

RUSSELL, J. L.—Royal Aircraft Establishment Report (Secret): Atmospheric Transmission Tests at Various Altitudes.

HULBERT, E. O.—J. Opt. Soc. Amer., 27, p. 377 (1937): Observations on a Searchlight Beam to 28 km.

JOHNSON, MEYER, HOPKINS, AND MOCK.—J. Opt. Soc. Amer., 29, p. 512 (1939): Observations on a Searchlight Beam.

ROCARD, Y.—"Rev. d'Optique," 11, p. 193 (1932): (Gives distribution of light scattered by the atmosphere, ground level.)

HULBERT, E. O.—J. Opt. Soc. Amer., 31 (7), p. 467 (1941): Optics of Atmospheric Haze (Gives distribution of light scattered by atmosphere, from observations on searchlight beam and otherwise, ground level).

WALDRAM, J. M.—"Illum. Engineer," 27, p. 311 (1934): Telephotometer.

COLLIER, L. J.—Trans. Illum. Eng. Soc. (London), III. (10), p. 141 (1938): Telephotometry.

APPENDIX I.

Meteorological Reports

SERIES I.

The following data refer to upper air ascents made by the Meteorological flight in the vicinity of the experiments. On no occasion was there any major change in conditions between the time of the afternoon and morning ascents.

(i)

May 1, 1941. 1530 *G.M.T.* (*Fig.* 11a.)
Temp. 15,000 ft., + 4 deg. F.
R. H. at 13,800 ft., 85 p.c.; at 15,950 ft., 100 per cent.
Haze top, 5,810 ft.
Visibility at 13,800 ft., good downwards and horizontally.
May 2, 1941. 0430 *G.M.T.*
Temp. 15,000 ft., + 4 deg. F.
R. H. 13,900 ft., 91 p.c.; at 16,050 ft., 100 per cent.
Visibility at 13,900 ft., good downwards and horizontally.

(ii)

May 2, 1941. 1630 *G.M.T.* (*Fig.* 11b.)
Temp. 18,000 ft., − 9 deg. F.
R. H. at 16,170 ft., 100 p.c. (Highest reading.)

Haze top, 10,100 ft.
Inversion { top, 24 deg. F., 10,100 ft. / base, 22 deg. F., 8,320 ft.
Visibility not reported.
May 3, 1941. 0530 *G.M.T.*
Temp., 18,000 ft., −6 deg. F.
R. H. at 11,970 ft., 87 p.c. (Highest reading.)
Visibility good downwards and horizontally.

Synoptic Situation

High pressure to the North with a gradient for easterly winds across the British Isles up to and beyond the level of the experiments. These conditions are somewhat unusual in regard to the persistence of easterly winds at high levels, but in other respects are not abnormal.

Series II.

Oct. 2, 1941. 1500–1630 B.S.T. (Fig. 11c).

Alt.	Temp.	R.H. %	Wind Deg.	Wind m.p.h.	
Surface	66°F.	65			
1,000 ft.	61	71	280	7	Haze top 4,000 ft.
3,000 ft.	54	90	290	10	Inversion :—
5,000 ft.	46	85	300	15	Base 5,280 ft., 45 deg.
10,000 ft.	44	70	350	45	Top 6,910 ft., 47 deg.
15,000 ft.	29	—	350	50	*Visibility*
20,000 ft.	8	—	340	50	*Height* *Vertical* *Horizontal*
25,000 ft.	−13	—	360	55	6,870 ft. Indifferent Very good
29,000 ft.	−29	—	360	60	10,470 ft. ,, ,, ,,
					14,540 ft. ,, ,, ,,

Anticyclone over Low Counties extending to Southern England. Light southerly or variable winds ; small amounts of cloud about 4,000 ft ; visibility good.

Oct. 3, 1941. 1530–1730 B.S.T. (Fig. 11d).

Alt.	Temp.	R.H. %	Wind Deg.	Wind m.p.h.	
Surface	64°F.	55			Haze top 3,000 ft.
1,000 ft.	60	75	080	12	Isothermal layer 45 deg.
3,000 ft.	50	60	080	15	Base 3,600 ft.
5,000 ft.	45	25	090	15	Top 5,140 ft.
10,000 ft.	37	30	090	20	*Visibility*
15,000 ft.	18	100	100	25	*Height* *Vertical* *Horizontal*
20,000 ft.	3	92	110	25	6,840 ft. Very good Very good
25,000 ft.	−18	95	090	20	10,430 ft. ,, ,, ,, ,,
29,000 ft.	−35	—	110	25	14,470 ft. ,, ,, ,, ,,

Anticyclone covering British Isles. Light north-easterly winds ; little or no cloud ; moderate to good visibility.

Oct. 7, 1941. 1530–1630 B.S.T. 1630–1800 B.S.T. (Fig. 11e).

Alt.	Temp.	R.H. %	Wind Deg.	Wind m.p.h.	
Surface	65°F.	92			
1,000 ft.	63	90	120	15	
3,000 ft.	61	70	140	20	Inversion nil.
5,000 ft	54	74	160	20	*Visibility*
10,000 ft.	36	63	210	25	*Height* *Vertical* *Horizontal*
12,000 ft.	32	90	210	30	6,850 ft. Bad Very good
15,000 ft.	20	—	220	35	10,430 ft. ,, ,, ,,
20,000 ft.	5	—	220	40	14,470 ft. ,, ,, ,,
23,000 ft.	−7	100	210	45	Wind veered 160 deg. to 200 deg. about 6,000 ft.

Anticyclone over North Sea. Light south-easterly winds ; small amount of cloud about 3,000 ft. ; visibility poor with local fog patches.

Note.—Upper air temperatures and humidities, inversions and heights from which visibility observations were taken are not from direct readings over each locality, but are interpolated from available data.

SERIES III.

HORIZONTAL VISIBILITY AT SURFACE.

Date	Time B.S.T.	Visibility Miles	Remarks
May 9, 1942 (Fig. 11g)	11.00	6–12 (probably	London smoke. Thick haze layer to 1,500 ft. and probably second haze top at 6,000 ft.
	12.00	4–6 nearer 6)	
	13.00	4–6	
May 19, 1942 (Fig. 11i)	10.00	12–18	Slight haze layer to 1,500 ft.; also possibly at 23,000 ft.
	11.00	18–32	
	12.00	18–32	
May 29, 1942 (Fig. 11k)	15.00	12–18	No haze layer.
	16.00	12–18	
	17.00	18–32	
May 31, 1942 (Fig. 11l)	11.00	12–18	Slight haze tops at 5,000 ft. and 21,000 ft.
	12.00	12–18	
	13.00	12–18	
June 1, 1942 (Fig. 11m)	11.00	6–12	Haze top 14,500 ft. and possibly slight haze top at 24,000 ft.
	12.00	6–12	
	13.00	12–18	

APPENDIX II.

Experiments with a Searchlight Beam.

After the experiments of Series I, when it was not certain that any further aircraft experiments would be possible, some experiments were made with the co-operation of R.R.D.E., in which measurements were made of the brightness of a searchlight beam, exposed vertically, from a distant station on the ground. A method was worked out by which the scattering coefficient at various heights could be deduced, on the assumption that the polar scatter indices occurring at various altitudes were substantially the same as had been found in the Series I experiments. The searchlight experiments were technically successful; the beam brightness was measured with both a visual telephotometer and by a method of photographic photometry and the scattering coefficients were deduced. Hulbert and others describe somewhat similar methods which were used to great heights in U.S.A.*

Later, however, it was possible to make the Series II and III experiments, and it became evident that the basic assumption was quite invalid. The polar scatter index, for a given scattering coefficient, varies so greatly—particularly at the angles concerned—that the method is unreliable. Since then another method of using a searchlight beam has been worked out and tried experimentally, which is likely to give reliable results for the lower layers of the atmosphere, say to 1,000 ft. or so.

*Hulbert, E. O., J. Opt. Soc. Amer., 27, p. 277 (1937). Johnson, Meyer, Hopkins and Mock, J. Opt. Soc. Amer., 29, p. 512 (1939).

APPENDIX III.

Measurement of Air-Ground Transmission During Daylight.

During the course of the balloon experiments a method was devised by Mr. S. S. Beggs and the author for obtaining the air-ground transmission during daylight, from observations from the air. If the air observer measures the brightness of a white and a nearly black target on the ground, and if simultaneous measurements of illumination are made at the ground, then the transmission of the air can be found; it is given by:

$$t_h = \frac{\rho_o(r_1 - r_2)}{R_o(\rho_1 - \rho_2)}$$

where r_1 and r_2 are the readings from

the air on two surfaces of reflection factors ρ_1 and ρ_2 respectively, and R° is a reading from the ground on a test surface of reflection factor ρ_o.

If only the ratio of the brightnesses of the white and of the dark targets are measured from the air, then the haze factor (the brightness of the veiling haze, expressed as a multiple of the ground brightness without the veiling haze) can be found, but in this case the transmission cannot be found.

This was tried from the balloon, using as targets the white sheet and the grass beside it. But for operational reasons the balloon could only be flown at dawn, and difficulties were found with the rapidly increasing daylight, the low-angle sun which resulted in uneven brightness of the curved sheet, and with the telephotometer, which was not adapted to high-brightness work. Given reasonable conditions and the proper instruments it could probably be done, though from an aeroplane telephotometry would be difficult. Schuil's telephotometer, which was developed later for use from aircraft in daylight, would greatly facilitate the measurements.

(A Summary of the above paper, together with an account of the subsequent discussion appears in the Transactions for June, 1945, pages 125—130.)

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